012142

THE PETROLOGY AND ALTERATION OF THE MOUNT NANSEN PORPHYR STOCK NEAR CARMACKS, YUKON TERRITORY

FILE COPY

1395 Ottawa Avenue,
West Vancouver, B.C.

April 14th, 1972

Dr. J. W. Murray,
Acting Head, Department of Geology,
The University of British Columbia,
Vancouver 8, British Columbia

Dear Dr. Murray:

I respectfully submit my thesis, "The Petrology and Alteration of the Mount Nansen Porphyry Stock and Adjacent Rocks, near Carmacks, Yukon Territory", in partial fulfillment of the requirements for the degree of Bachelor of Science, in Honours Geology.

Yours truly,

Robert A. Dickinson

This thesis meets the standards and requirements of the Department of Geology.

____

Thesis Supervisor

TABLE OF CONTENTS

Page

LIST OF PLATES

ABSTRACT

A study of the Mount Nansen area, south-central Yukon, has shown that its surface geology is similar to that of many porphyry copper camps. The area is part of a northwest trending belt of Mesozoic to Tertiary calc-alkaline igneous rocks. Igneous rocks intrude and overlie metamorphic rocks of uncertain age. At least three periods of igneous activity have occurred.

Rocks formed during the first period of igneous activity are mainly extrusives and are called the Mount Nansen group. Rock types of this group are commonly andesite porphyry and andesite flow breccia. A hypabyssal hornblende monzonite porphyry unit occurring as a sill and dykes has been included in this group on the basis of its mineralogy. The formation of this group probably started in Jurassic time and may have extended into the early Tertiary.

A second period of intrusion produced two batholithic rock units. Hypersthene-quartz diorite is found peripheral to a more areally extensive unit, of a quartz monzonite-adamellite composition. The quartz monzonite unit intrudes the quartz diorite but these units can probably be considered comagmatic. Rocks of this second igneous period are of mid-Cretaceous age.

A multiple phase porphyry intrusion, of late-Cretaceous to early-Tertiary age, is spatially related to the batholithic rocks. The earliest and closely associated phases include units of biotite-quartz monzonite and quartz-monzonite porphyry.

A later sub-volcanic phase of rhyodacite porphyry has probably intruded at a higher tectonic level. Porphyritic dykes and extrusive outliers of rhyolite porphyry appear closely associated with this final period of intrusion.

The porphyry units have been brecciated and fractured. Brecciation may be due to the explosive action of confined late stage volatiles in sub-volcanic cupolas. Areas of fracturing have localized hydrothermal solutions that probably have differentiated from the porphyry magma. Advanced argillic and phyllic alteration mineral assemblages are found in these brecciated core areas. Successively surrounding intensely altered cores are irregular halos of argillic and propylitic alteration. Supergene and deuteric alteration may have increased the extreme amount of argillization and propylitization found in these outer zones. The alteration pattern has been produced mainly by a decreasing, temperature and $\frac{cation}{H^+}$ activity ratio of the altering hydrothermal fluids.

Post-alteration faulting has modified the halo pattern of alteration mineral assemblages.

INTRODUCTION

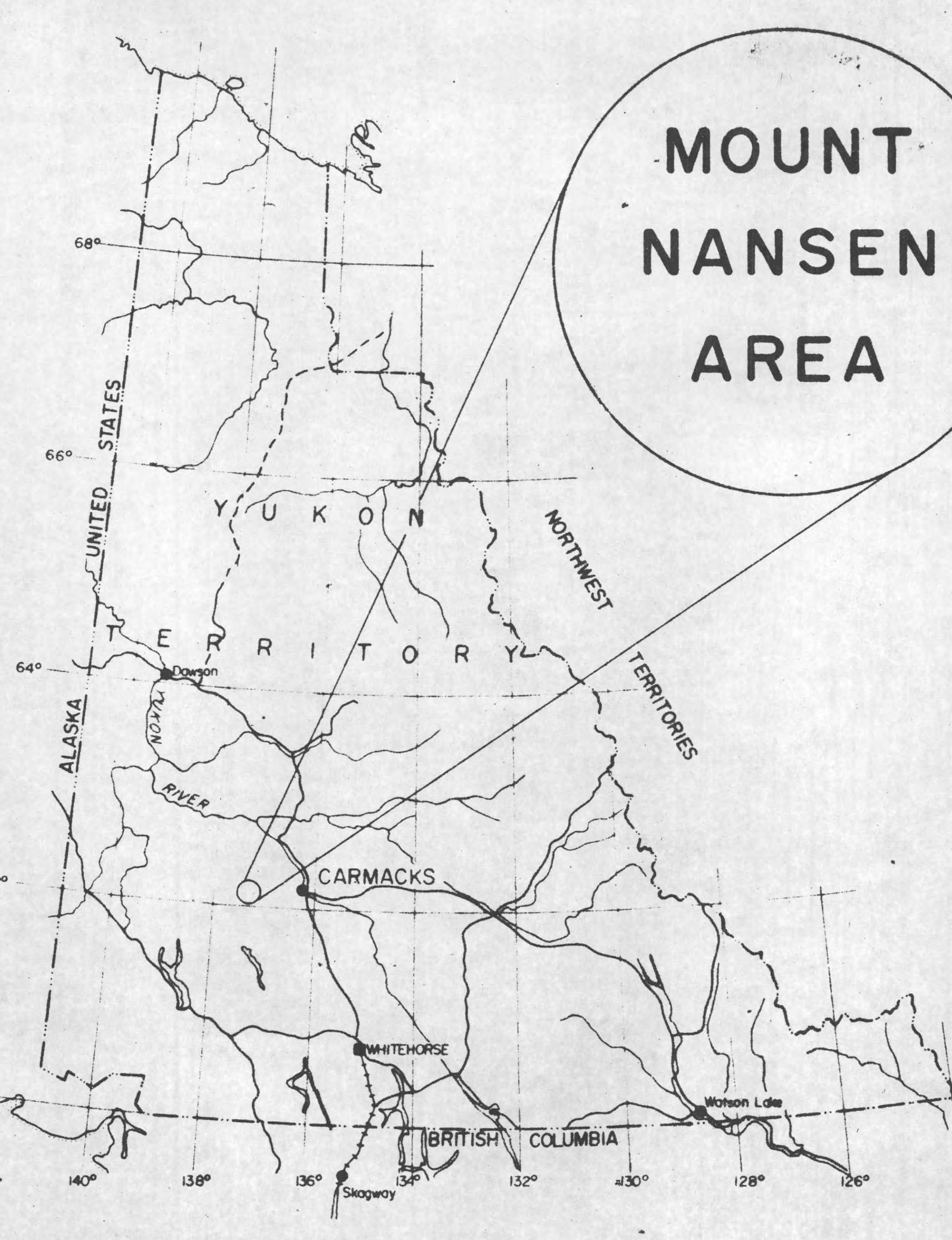
Foreword

The Mount Nansen area has potential for porphyry copper-type mineralization. The geological environment is similar to that of the large copper deposits of the south-western United States. The author investigated this area during the 1970 field season while employed by Cyprus Exploration Corporation Limited. Several features common to porphyry copper deposits were noted. Two of these are described in detail within this thesis. They are:

1. the petrology of an early Tertiary, composite porphyry stock and adjacent rock types.

2. the zonal distribution of hydrothermal alteration products, including the possible effects of a supergene imprint.

Outcrop in the Mount Nansen area is less than 5%. Recognition of the various rock types, especially the intrusives and their relationships is essential in coming to an understanding of the complex geology. Coupled with the lack of outcrop, many of the primary mineralogical and textural features of the rocks are obscured by hydrothermal and supergene activity. To assist with field work, petrographic, x-ray diffraction and staining studies were made to enable a better understanding of the geology of the Mount Nansen area. A geological and alteration map shows the results of these studies.



THESIS LOCATION MAP

SCALE : 1" = 100 MILES

FIG. 1

Location and Access

The thesis area is located in south-central Yukon Territory, 115 miles northwest of Whitehorse and 35 miles west of Carmacks (Figure 1). It encompasses 18 square miles between $137^{\circ}07'$ to $137^{\circ}16'$ west longtitude and $62^{\circ}03'30''$ to $62^{\circ}06'30''$ north latitude.

Access to the Mount Nansen area is by a 45 mile long dirt road branching westerly at Carmacks from the Whitehorse-Mayo Highway. A four wheel drive vehicle is required to reach the area except during dry weather conditions.

History

The first geologist to visit the Mount Nansen area was D.D. Cairnes in 1914. He examined the gold placers on Nansen and Victoria Creeks and made a reconnaissance survey of the region. His map and report appeared in the Geological Survey of Canada, Summary Report for 1914. H.S. Bostock also of the G.S.C. undertook a reconnaissance survey of the Carmacks district in 1932, 1933 and 1934. He compiled a report and map which was published as Memoir 189.

Mining in the area has been intermittent. All the creeks were staked for placer gold by miners enroute to the Klondike. Most claims have lapsed and in all, only from $5,000 to $7,000 in gold is thought to have been obtained from the Nansen district (Cairnes, 1914).

In 1943, prospectors located Pb-Ag-Au veins one mile south of the thesis area. These veins were later explored by Peso Silver Mines Ltd. On the basis of this exploration, Mount Nansen Mines Ltd. put a 400 t.p.d. mill into production in 1968. The production period started September, 1968 and ended April, 1969 as a result of poor recovery of the Ag and Au values.

ACKNOWLEDGEMENTS

The writer is indebted to J.B.P. Sawyer, Manager - Canadian Exploration, of Cyprus Exploration Corporation Limited, for permission to write this thesis, and financial assistance for the preparation of thin sections and maps. Special thanks go to P.F. Lewis whose work with the author in the field, and knowledgeable suggestions were found to be invaluable.

The author wishes to thank Dr. E.P. Meagher for his supervision of the thesis, and untiring help with x-ray diffraction work.

Gratefully acknowledged is the assistance of Dr. P.B. Read and C.I. Godwin, with thin section and alteration study.

GEOMORPHOLOGY

Glaciation

The thesis area lies at the southwest end of the Dawson Range. The Dawson Range is a northwest trending belt of gentle summits within the Yukon Plateau. Most of the Dawson Range escaped glaciation during Pleistocene time and is characterized by gently rolling hills, V-shaped valleys and the absence of lakes. These features are consistent with a physiographically mature surface.

Very little evidence of glacial erosion could be found in the Nansen area although the area lies close to the western margin of Pleistocene glaciation (Figure 2). Cairnes (1914) noted glacial boulder-clay in Nansen Creek while examining gold placers in the area. He postulated that since this area was on the edge of a late Wisconsin (McConnell) advance, the boulder-clay represented the effect of glacial tongues filling the larger valleys. Hence ice action would probably not have extended more than a few hundred feet up the sides of the Nansen Creek valley and consequently the glacial deposits would not reach far above the present valley bottom.

Bostock (1966) and Hughes (1969) believe the boulder-clay to be related to a pre-McConnell advance to which they have given the informal name of Nansen advance. Bostock (1966) reports visiting a section at 4,600 feet elevation on the head of Discovery Creek. The section shows soil at top, underlain by angular rubble and then by coarse rotten gravel that lay on bedrock. This gravel, he believed, belonged to the glaciation that left the boulder-clay. Bostock (1966) further assumes that the high elevation at which the gravel occurs indicates that the glaciation probably spread beyond the locality where it has been found. However, lack of noticeable glacial topographical features suggests that very little glacial erosion occurred.

Plate 1. Section exposed in Discovery Creek. Glacial gravel is cemented with limonite.

Climate in recent times has been both cold and arid. Mean annual temperature is in the range of 20 - 30° Fahrenheit and annual precipitation is 8 - 14 inches. The area is permafrost covered.

Topography

The Mount Nansen area is characterized by gently rolling hills. The maximum relief in the area is 2,490 feet from the altitude of 3,400 feet at the lowest point in the Nansen Creek valley to 5,000 feet on Mount Nansen. A central ridge averaging 4,500 feet in altitude trends northwest across the area. It slopes off gently to Nansen Creek on the west and the headwaters of Victoria Creek to the east.

Topography indicates that at higher elevations glacial erosion has not occurred except possibly by glacial tongues in the major creek valleys.

Geological controls such as rock type, hydrothermal alteration and fracturing have influenced the trellis type drainage pattern. Resistant Mount Nansen volcanics form craggy bluffs which almost completely surround a topographic low of hydrothermally altered intrusives. Strongly silicified areas within these intrusives are left as dome structures. Creeks generally trend north, northwest and northeast following the predominant fracture trends of the area. Nansen Creek, Discovery Creek and the East Fork are examples.

Timberline is at an altitude of approximately 4,000 feet. The lowest sections of the area are covered thinly by spruce, birch and poplar. Thick brush extends above timberline but the higher areas are covered only by grass.

Plate 2. View north from the head of Discovery Creek. Higher peaks are volcanics. The three domes in middle distance are silicified porphyry intrusives.

Plate 3. View south from northeast corner of thesis area. Volcanic outcrop in foreground. Topographically low weathered intrusives in background.

REGIONAL GEOLOGY

Lithologies

The area is part of a northwest trending belt of Mesozoic to Tertiary calc-alkaline igneous rocks. The igneous rocks intrude and overlie metamorphic rocks of uncertain age.

The oldest rock units in this belt are metasediments, and granite and diorite gneisses comprising the Yukon group. The oldest members of this group, which are possibly Cambrian or older in age (Bostock, 1936), consist largely of quartz-mica schist, hornblende schist with lesser amounts of quartzite, gneiss and limestone. Succeeding these are a similar series of Palaeozoic schists, quartzites, limestone and greenstones. Bostock (1936) believes both members were cut by granite and diorite gneisses which were metamorphosed at the same time as the sediments.

The Yukon group is overlain by the Triassic, Lewes River series, Jurassic Laberge series and the Jurassic-Cretaceous Tantalus formation. These are mainly clastic sequences of shale, conglomerate, limestone, tuffaceous sandstone and minor coal measures. These rocks are not found in the map area.

Unconformably overlying the Yukon group in the map area is the Mount Nansen group. The rocks of this group include basic volcanic lavas, ranging in composition from basalt to dacite. Also included in this group are flow breccias, tuffs, small areas of sediments, and small dioritic bodies, associated with the lavas. The volcanics in the map area are predominantly of the Mount Nansen group and are typically porphyritic andesite. The Mount Nansen group is considered by Bostock (1936) to have formed in late Jurassic or early Cretaceous time.

The Mount Nansen volcanics have been invaded by a succession of Mesozoic plutonic rocks contemporaneous with the Coast Range intrusives. The intrusives trend northwest-southeast and emplacement is probably related to a regional scale, tectonic feature. They are composed of a great variety of rock types ranging from diorite to syenite and granite. Diorites are thought to be the oldest of the intrusives followed by syenites. The most extensive intrusions and probably the youngest of this group are rocks of a granodiorite-adamellite composition. These latter granitic rocks make up a large portion of the thesis area.

A final period of intrusion took place in late Cretaceous to early Tertiary time. Small hypabyssal stocks were formed and appear spatially related to the granitic intrusives of the main Mesozoic batholithic event. Most of them are fine to medium grained, porphyritic, acid rocks; largely quartz porphyry, granite porphyry, or granophyre with some rhyolite. A composite intrusion of this age is centrally located in the thesis area surrounded by outliers of rhyolite.

The youngest rocks in the region are the Carmacks volcanics. The lavas are mainly andesites, but range in composition from basalts to dacites, trachytes and rhyolites (Bostock, 1936). These plateau basalts unconformably overlie all the older formations. The Carmacks volcanics are not found in the thesis area and have been completely eroded exposing many of the described rock units (Figure 2).

Mineralization

Most of the mineralization found in the Dawson Range is thought to be related to the late Cretaceous-early Tertiary acid, sub-volcanic intrusives. Placer gold deposits now of non-economic quantities are found in streams leading off the stocks. Nansen Creek and Back Creek have been worked for gold since 1910 (Cairnes, 1914). Canadian Creek leading from the Casino stock, some 65 miles to the northwest of the Nansen area was staked for placer gold in 1911 (Cairnes, 1917).

Pb-Ag-Au vein deposits, such as those found zonally around the Casino stock are thought to be genetically related to the early Tertiary intrusives (Godwin and Phillips, 1970).

Porphyry copper type mineralization is also being actively looked for in areas where these stocks have been exposed. Since most of the Dawson Range has not been glaciated, supergene enriched zones can be expected. The Casino deposit and the Williams Creek prospect (Abbot, 1971), 24 miles north-east, are examples of porphyry copper mineralization located in the Dawson Range.

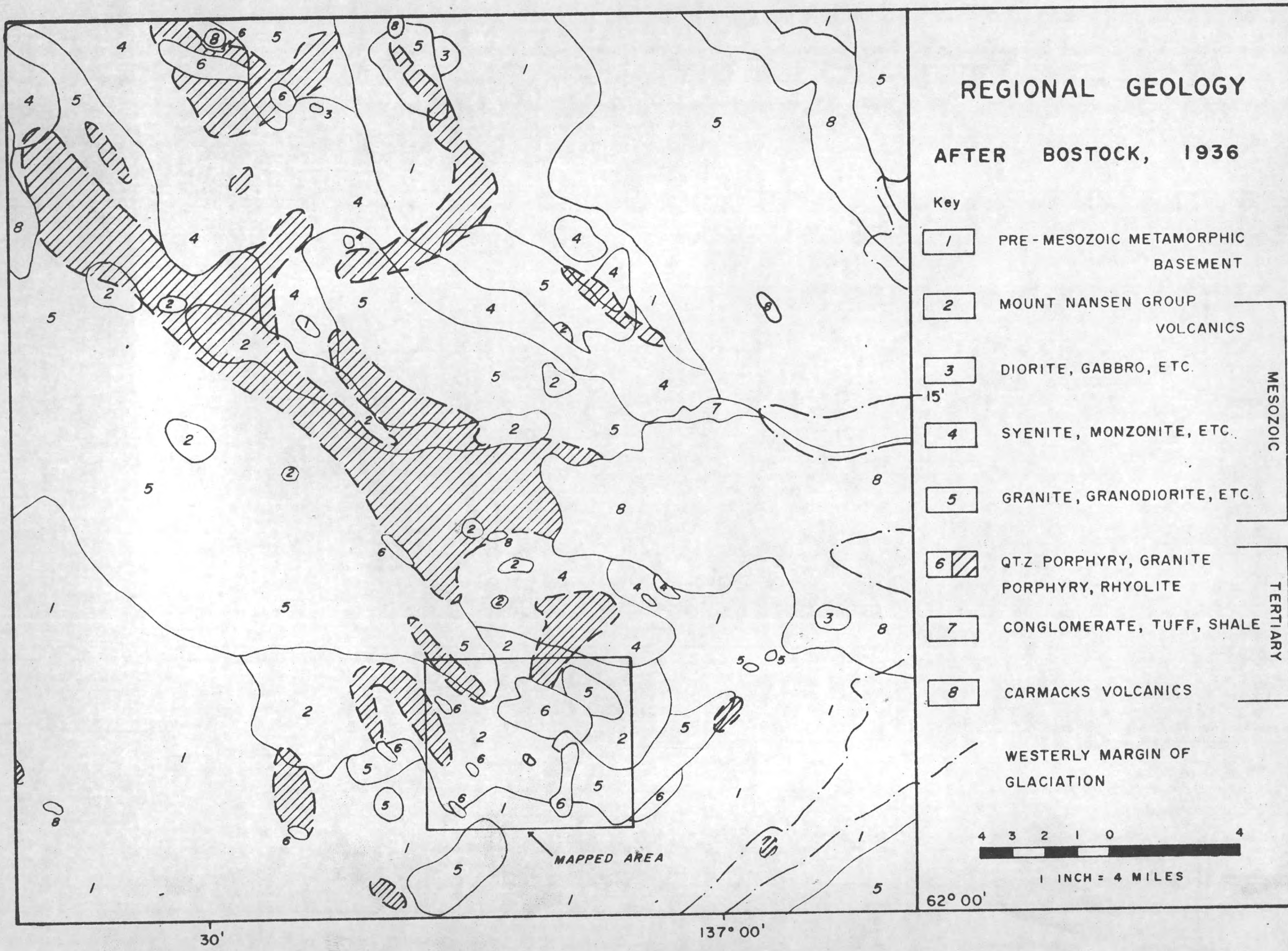

REGIONAL GEOLOGY
AFTER BOSTOCK, 1936
Key
1 PRE-MESOZOIC METAMORPHIC BASEMENT
2 MOUNT NANSEN GROUP VOLCANICS
3 DIORITE, GABBRO, ETC.
4 SYENITE, MONZONITE, ETC.
5 GRANITE, GRANODIORITE, ETC.
MESOZOIC
6 QTZ. PORPHYRY, GRANITE PORPHYRY, RHYOLITE
7 CONGLOMERATE, TUFF, SHALE
8 CARMACKS VOLCANICS
TERTIARY
WESTERLY MARGIN OF GLACIATION
4 3 2 1 0 4
1 INCH = 4 MILES
15'
62° 00'
MAPPED AREA
30'
137° 00'

Fig ii

ROCK UNITS

Field Mapping Procedure

Outcrop in the Mount Nansen area is less than 5%. Float had to be mapped as representative of bedrock to a large extent. Road cuts and old slumped trenches gave some added control. The main variables considered when mapping float were:

a) angularity of float sample

b) size of float

c) abundance of rock type

d) grade of slopes

e) occurrence of rock type uphill

f) disappearance of rock type on uphill grade

Rock type was obscured in all valley floors due to downslope solifluction of ridge rocks, and mapping in these areas was merely conjecture.

Faults and/or fractures were located by geophysical, geological and air photo data. Several zones of fault gouge and shearing were noted and these are shown as being defined fractures on the accompanying map. There was not enough geological control to map offsets.

Twelve distinct rock types were observed in the Mount Nansen area and their description and distribution follows. The rocks are described in probable order of decreasing age. Following the description of the rocks, an inferred stratigraphic order and interpretation is presented.

Lithologies and Petrology

Yukon Group Metamorphics - Unit A

The Yukon group is of uncertain age but is generally considered early Palaeozoic or Precambrian. The group comprises the only metamorphosed rocks of the area.

Exposure of the Yukon group metamorphic rocks is limited in the map area, although they crop out over a considerable area just to the south. A small sub-circular window of metasediments is exposed, probably as a result of block uplifts in the volcanic cover south of Discovery Creek. The float in this exposure is predominantly hornblende gneiss and metaquartzite. They are high grade, regionally metamorphosed rocks with a sedimentary origin. The hornblende gneiss has dark green, hornblende rich layers (1 - 2 mm thick), alternating with white felsic layers (1 - 2 mm thick).

Observed under the microscope, the dark green layers consist of euhedral hornblende (1 mm) and plagioclase (An_{30}). The white layers consist of fine grained quartz, plagioclase and some potash feldspar. The metaquartzite is cream-white coloured, aphanitic and structureless.

No idea of the regional structure of these rocks could be gained. Bostock (1936, p. 17) believes that the trend of folding in the Mount Nansen area is north 60° east with strata dipping up to 30°.

Plate 4. Hornblende gneiss.

Mount Nansen Group - Units B, C, D

The Mount Nansen group is the most areally extensive rock type of the area. It includes extrusives and sub-volcanic sill and dyke intrusives. A marked feature of the extrusive rocks is their resistance to erosion, so they form high hills with long, steep slopes leading down to bordering valleys. All of the higher hills are covered by this group. They derive their name from Mount Nansen, an exceptionally prominant topographic feature at the northwest corner of the map area. Three rock types of this group crop out in the Mount Nansen area. They are shown on the geology map (Appendix 3) as follows; andesitic flow breccias (B), andesite (C), and hornblende monzonite porphyry (D). The breccias and andesite occur as flows and cover much of the underlying Yukon group and later extrusives. Hornblende monzonite porphyry occurs as a sill and dykes. Dykes of this unit trend north and northeasterly. The author believes they represent feeder dykes to the extrusives, because of thin close spatial and compositional relation. Bostock (1936) believes this group to have formed during late Jurassic to early Cretaceous time.

Unit B is andesite flow breccia and is found south of Discovery Creek. It is composed of fragments of Mount Nansen andesite and minor Yukon group metamorphics, in an aphanitic andesite matrix. Fresh surfaces are dark grey-green while weathered surfaces are light grey-green. Fragments are usually distinguished from the matrix by being darker in colour. The lithic fragments are commonly of pebble size (4 mm - 64 mm), but may be larger. Following Krumbein (1963, Appendix 1), the fragments usually are subangular having a sphericity of 0.7 and a roundness of 0.3. The individual fragments are rarely touching each other. Andesitic matrix makes up most of the rock.

Thin section examination of typical andesite flow breccia reveals porphyritic andesite fragments in a microcrystalline matrix of andesite composition. The fragments are composed of plagioclase (An_{30-40}) and hornblende that frequently has been replaced by clinozoisite and chlorite. The plagioclase phenocrysts average 0.5 mm in length. Microlites of plagioclase and secondary minerals after the mafics form the groundmass of the fragments.

The matrix of the rock is microcrystalline. It is commonly composed of plagioclase, ilmenite, leucoxene, chlorite, epidote and possibly remnants of pyroxene.

Unit C is typically porphyritic andesite, but minor basalt is included in this unit. The andesites are dark green coloured and speckled with white plagioclase phenocrysts on fresh surfaces, while bleached greenish-grey on weathered surfaces.

A microscopic investigation reveals that the porphyritic andesites are composed of plagioclase (An_{30-40}), hornblende and magnetite (3%).

Plagioclase, commonly 1 mm. in length, is typically saussuritized, broken, and exhibits normal oscillatory zoning. Sericite commonly flecks the phenocrysts in rock samples located near later intrusions. Plagioclase phenocrysts form approximately 40% of the rock. Anhedral hornblende, some possibly a replacement product of pyroxene, has altered to aggregates of green biotite and in some instances chlorite, epidote and magnetite. The microcrystalline matrix is composed of anhedral plagioclase, chlorite, epidote and hornblende.

Plate 5. Mount Nansen extrusives. Two examples of flow breccias (left) and porphyritic andesite (right).

Unit D is a hornblende monzonite porphyry. It occurs as approximately 25 foot wide dykes at the northwest corner of the map. Widespread float was also mapped along the Wheeler Fault south of these dykes. This float was thought to represent a sill-like body in this area.

The rock is named a hornblende monzonite porphyry rather than a more general field term hornblende porphyry to indicate that the rock is mineralogically not related to the more acid intrusives of late-Cretaceous age (Appendix 2).

The hornblende monzonite porphyry is a mesocratic rock composed of phenocrysts of black columnar hornblende (up to 5 mm) and finer grained plagioclase (1 - 2 mm), set in a microcrystalline greyish white matrix. The rock is moderately magnetic. Weathered surfaces are thinly coated with reddish brown, hematitic limonite, which is a result of the oxidation of magnetite.

Examination of several thin sections showed this porphyritic rock to be composed of andesine (30%), potash feldspar (35%), hornblende (15%), and minor quartz (5%). Commonly, chlorite, epidote, biotite, apatite, and magnetite are found as accessory minerals and deuteric alteration products.

Euhedral hornblende phenocrysts are often twinned, have an extinction angle ($c \wedge Z$) of 18°, and a pleochroic scheme of deep green (Z) to pale green (X). The hornblende is usually altered (up to 50%) to chlorite, epidote and magnetite. In one section (C-83) hornblende is being replaced by a felty mass of green biotite. Plagioclase (An_{45-55}) phenocrysts are generally subhedral and broken. They are locally normally zoned and commonly saussuritized to a mixture of albite, epidote, and chlorite. The microcrystalline matrix is made up of interstitial potash feldspar and small amounts of quartz. Myrmekite is found marginal to the potash feldspar in one section and is probably due to a late magmatic replacement reaction of potash feldspar (Williams 1954, p. 20).

Plate 6. Hornblende monzonite porphyry.
Unstained and stained pair.

Mesozoic Intrusive Rocks - Units E, F

The Yukon and Mount Nansen groups are intruded by a variety of igneous rocks which according to Bostock (1936), vary from dioritic to granitic composition. The age of the intrusion has been postulated to be late Jurassic to early Eocene, and the intrusion itself has been related to the Coast Range intrusion sequence (Bostock, 1936). Bostock's postulation has been confirmed by a recent K-Ar age determination from granodiorite samples collected on the property of Casino Silver Mines Ltd. which yielded Cretaceous ages of 95 my. and 99 my. (Findlay, 1969, p. 27).

Two distinct rock types form a northwest trending batholith in the central thesis area. These are hypersthene-quartz diorite (E) and quartz monzonite (F). Unit E is found as small irregular bodies peripheral to Unit F. Although no contacts were observed in the field, several float samples with quartz monzonite intrusive into hypersthene-quartz diorite were found, indicating the quartz monzonite (F) is the younger unit.

Unit E is a mesocratic, fine to medium grained, equigranular hypersthene-quartz diorite. It is recognized in the Mount Nansen area by being highly magnetic, non-porphyritic and fine to medium grained.

The rock exhibits a fine grained hypidiomorphic-granular texture in thin section. Mineralogy of the rock is andesine (50%), potash feldspar (10%), biotite (10%), hypersthene (10%), and hornblende (10%). Accessory minerals are magnetite (2%) and minor apatite. Common deuteric alteration minerals include biotite, chlorite, hornblende and actinolite.

Plagioclase (An_{40-44}) is typically subhedral and broken. Some of the smaller laths are normally zoned. Larger plagioclase crystals measure up to 1 mm. Hypersthene crystals (1 mm) are characterized by their pink pleochroic scheme and parallel extinction. In most sections examined, hypersthene is being replaced extensively by actinolite. Actinolite has a fibrous habit where it replaces the orthopyroxene along fractures. Two biotites are commonly present, one primary and the other of deuteric origin. Primary biotite laths (1 mm) are anhedral and are strongly pleochroic. The pleochroic scheme is deep red brown (Z) to faint tan brown (X). Secondary biotite is brownish green, has strong absorption and very little pleochroism. Anhedral orthoclase (.5 mm) poikilitically enclose all primary minerals. Quartz fills irregular interspaces between grains.

Plate 7. Hypersthene-quartz diorite

Unit F is the most areally extensive rock type of this group. It is medium to coarse-grained granular rock composed of plagioclase (4 mm), quartz (3 mm), orthoclase (2 mm), hornblende (3 mm), and biotite (2 mm).

Under the microscope the quartz monzonites have a hypidiomorphic-granular texture and are composed of andesine (40%), orthoclase (20%), quartz (15%), hornblende (10%), biotite (5%), and minor zircon. Common secondary components are magnetite, sphene, chlorite, epidote, and sericite. Locally the amounts of quartz and biotite are variable. Quartz in some samples ranges up to 25% of the volume of the rock. There does not appear to be any distinct zonal trend. Some of the more quartz rich samples were located several thousand feet away from the acid porphyritic units that will be described next. Locally, the biotite/hornblende ratio changes drastically. In general, biotite>hornblende north of the East Fork while hornblende>biotite in the quartz monzonites exposed to the south of Discovery Creek.

Plagioclase (An_{32-40}) is subhedral and some of the larger crystals show normal oscillatory zoning. Euhedral biotite is strongly pleochroic. Hornblende is light green, euhedral and has an extinction angle ($c \wedge Z$) of 18°. Quartz and orthoclase are interstitial to all other grains. Most of the quartz monzonites have been propylitized due to their spatial relation with hydrothermally altered porphyritic intrusives. Alteration will be described in detail in a later section.

Plate 8. Quartz monzonite, unstained and stained pair

Late Cretaceous to Early Tertiary Porphyry Intrusives and Extrusives - Units G, H, I, J, K

All of the previously described rock types are intruded by what the author believes is a composite stock. Three texturally and mineralogically distinct porphyritic phases form a northwest trending, elongate body centrally located in the thesis area. The stock is irregular in plan, with its long axis averaging two miles and its shorter northeast axis averaging one mile. The three phases determined to date include biotite-quartz monzonite (G), quartz monzonite porphyry (H) and rhyodacite porphyry (I). The former two rock types are probably earlier, and are located peripheral to the main exposure of rhyodacite porphyry. The rhyodacite porphyry also occurs as several small plug or dyke-like bodies which appear to cut all the earlier rock types, although no contacts were found in the field. Unit J is quartz-feldspar porphyry. This rock type is found only as dykes. The dykes cut the Mount Nansen volcanics and trend north and northeasterly. Extrusive rhyolites, and rhyolitic tuffs exposed in the area are probably a surface expression of this hypabyssal igneous activity. Porphyritic units are often so intensely hydrothermally altered, one rock type cannot be determined from another.

Porphyritic dacites from the Casino deposit comparable in texture and mineralogy to the rhyodacite porphyry have been dated by K-Ar methods at the University of British Columbia. A Palaeocence age of 69 $\pm$ 3 my. was obtained for one sample while a coarser-grained variety yielded a late Cretaceous age of 71 $\pm$ 3 my. (Phillips and Godwin, 1970).

Unit G is a leucocratic, medium-grained, granular, biotite-quartz monzonite. Minerals easily identified with the unaided eye are plagioclase (2 - 3 mm), quartz (1 mm), potash feldspar (1 mm), and biotite (1 mm). Plagioclase crystals tend to be porphyritic. A finer grained cream coloured groundmass makes up about 25% of the total volume of the rock. The rock is distinguished in the field by its apparent lack of prominent quartz phenocrysts and a "salt and pepper" appearance caused by an regular distribution of biotite.

Under the microscope the biotite-quartz monzonite is found to be composed of orthoclase (35%), quartz (25%), plagioclase (25%), and biotite (10%). Common accessory minerals are apatite (2%), zircon, and pyrite. Predominant secondary minerals are chlorite, carbonate, sericite, magnetite and albite. Plagioclase phenocrysts are anhedral to subhedral and have normal oscillatory zoning. More calcic zones are usually preferentially altered. The ragged rims are overgrown in some instances with alkali feldspar. Quartz crystals are deeply embayed and some have minor overgrowths. Biotite is usually rimmed by chlorite. Both apatite and zircon are euhedral. The fine grained groundmass is predominantly potash feldspar.

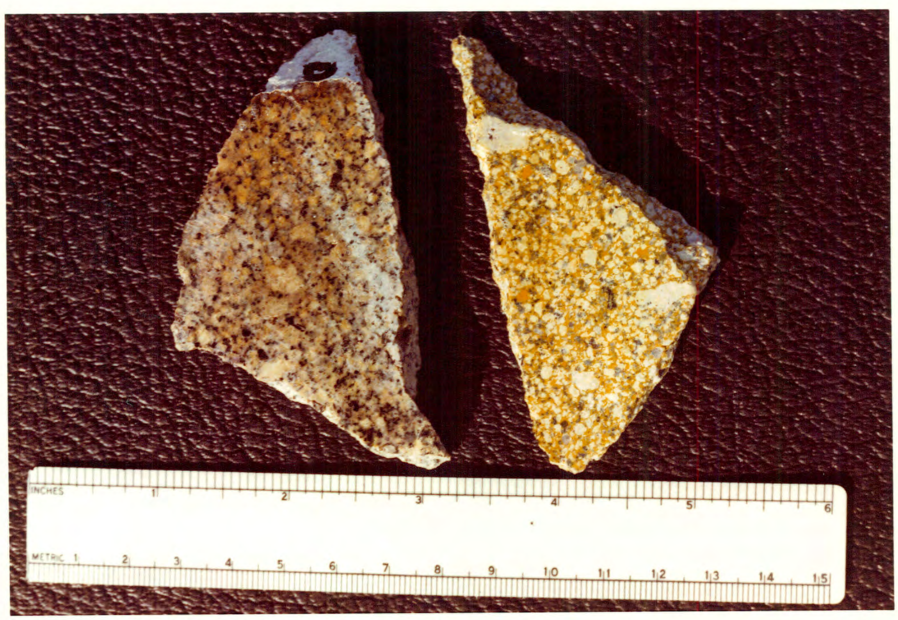


Plate 9. Biotite-quartz monzonite, unstained and stained pair

Unit H is found along the banks of Eva Creek. It is a cream white, quartz monzonite porphyry, with a microcrystalline matrix that makes up 50% of the total rock volume. This quartz monzonite is probably closely associated with Unit G. However, unlike the biotite-quartz monzonite, it has large rounded quartz phenocrysts (3 - 5 mm) and a greater amount of matrix. Weathered surfaces are usually thinly stained with a mixture of jarosite and goethite and the feldspars are often washed out. The rock becomes gradationally fine-grained to the west.

Examination of several thin sections of this rock type showed it to be composed of oligoclase (20%), orthoclase (50%), quartz (20%), and chlorite (10%). The chlorite has replaced biotite and probably minor hornblende. Accessory minerals are pyrite and apatite. Common products of hydrothermal alteration are chlorite, leucoxene, epidote, and sericite. Jarosite is found as a supergene mineral rimming pyrite. Plagioclase (An_{26-32}) is typically subhedral and flecked with sericite. Quartz phenocrysts are fractured, resorbed and some show faint overgrowths. Orthoclase is anhedral to subhedral and commonly poikilitic. Leucoxene (bright white under reflecting light) is always associated with chlorite. The microcrystalline matrix is predominantly potash feldspar.

Plate 10. Quartz monzonite porphyry, unstained and stained pair

Unit I occupies a central core area and is probably the youngest of the intrusives. Following Stringham (1966), the classification rhyodacite porphyry is used for this rock unit to indicate phenocrysts are prominent but subordinate (less than 50%) to an aphanitic groundmass. Large white potash feldspar (7 mm), white plagioclase (3 mm), and grey, rounded quartz (3 mm) phenocrysts are randomly set in a grey microcrystalline matrix. Minor, finer-grained mafics can also be observed in the field.

Optically, thin sections of relatively fresh rhyodacite, show that the subhedral orthoclase phenocrysts are always poikilitic. They enclose grains of sphene, biotite, hornblende, apatite, plagioclase and quartz. Plagioclase phenocrysts typically exhibit normal oscillatory zoning and are broken. The cores are An_{40} while outer zones tend to be An_{30}. Some of the plagioclase poikilitically encloses biotite. Quartz phenocrysts have a bypyramidal habit but are always deeply embayed. Biotite is anhedral and has a pleochroic scheme of deep brown (Z) to yellowish tan brown (X). The microcrystalline matrix of fresher samples is often made up of bright green uralite (after hornblende), quartz, andesine, and lesser amounts of potash feldspar. The matrix makes up 70% of the rock's total volume.

Plate 11. Examples of rhyodacite porphyry. Extreme right sample unstained.

Unit J is a quartz-feldspar porphyry. This rock is found as narrow dykes cutting the Mount Nansen andesites in the northern and western parts of the area.

The quartz-feldspar porphyry is composed of rounded, fractured quartz phenocrysts (2 mm), white plagioclase phenocrysts (2 mm), and finer-grained, bright green, chloritized mafics, set in a purplish microcrystalline matrix. The matrix makes up at least 50% of the rock. The weathered surface is reddish brown. Feldspar phenocrysts are commonly completely weathered out.

Under the microscope the rock is composed of potash feldspar (50%), plagioclase (20%), quartz (15%), chlorite (10%), and epidote (5%). Accessory minerals include apatite (1%) and opaques (1%).

Phenocrysts of plagioclase and quartz are subhedral. Commonly the plagioclase is extremely dirty looking and is probably replaced by clay. Quartz has a square habit suggesting a B-quartz crystal structure. All mafics have been completely replaced by chlorite and epidote. These minerals appear pseudomorphic after biotite. Apatite is typically euhedral. The microcrystalline matrix of this unit is completely potash feldspar.

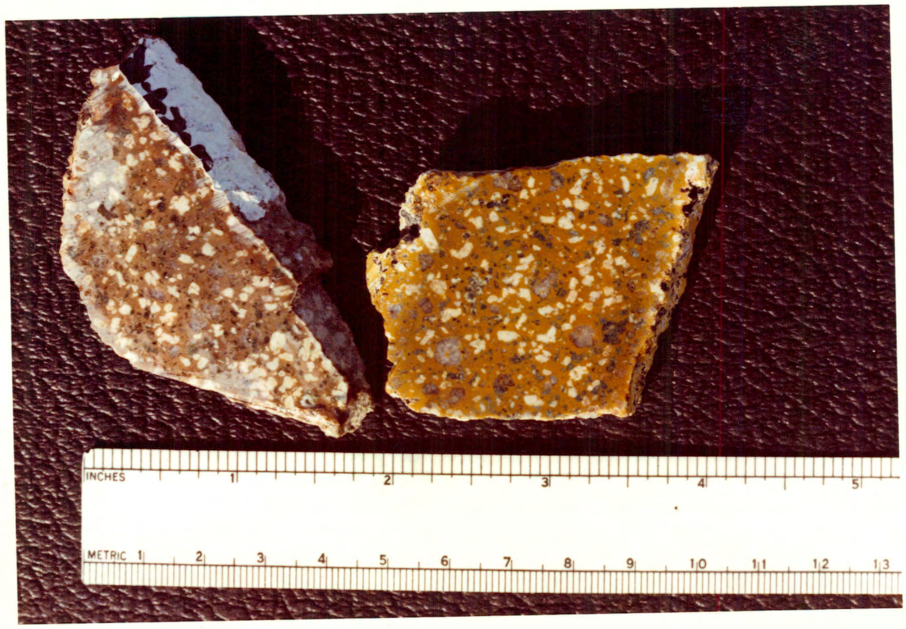


Plate 12. Quartz-feldspar porphyry.
Unstained and stained pair.

Unit K consists of several texturally variable, acidic extrusive rock types. Included are rhyolite tuff, rhyolite, and rhyolite porphyry. All varieties of this unit are white cream coloured. Most are cryptocrystalline with small phenocrysts of feldspar (1 mm) that are always completely replaced pseudomorphically by a kaolinite group mineral. There are no mafics present. Tuffs are typically irregularly banded (up to 4 mm).

Plate 13. Rhyolite porphyry, rhyolite tuff

Tourmaline Breccia - Unit L

Spatially associated with rhyodacite porphyry are two small sub-circular exposures of quartz-tourmaline cemented breccia. Maximum diameters of the exposure are 600 feet. Included in this unit is a small outcrop of breccia found south of Discovery Creek in the Mount Nansen volcanic cover. It consists of angular andesite and rhyodacite porphyry fragments in a quartz matrix. It is included in this group as it is probably a nearer surface expression of the same processes that formed the two tourmaline breccias. All breccias are spatially associated with fracture lineaments; data coming from geophysical, geological and air photo interpretation.

Large amounts of pyritized, granular fault gouge were found 200 feet west of the largest and centrally located tourmaline breccia body. However, unlike the highly altered breccia fragments, the gouge grains show little evidence of hydrothermal alteration. Feldspar grains are unaltered. Fragments within the breccia show little evidence of cataclastic shearing. These facts indicate the fault is not related to the genesis of the breccia. Both the faulting and brecciation suggest a zone of weakness in this area.

Other non-tourmalinized breccias may occur in the area of late stage porphyry intrusions. Three silicified dome structures trending north-northwest within the porphyry area may indicate brecciation at levels not exposed. Sample D-90 taken from the west flank of the largest of these structures is composed of a high percentage of fractured, angular quartz grains and may be a microbreccia. However, no fragment outlines could be distinguished in hand specimen or thin section.

The tourmaline breccia consists of intensely altered fragments of rhyodacite porphyry and possibly some quartz monzonite, in a black coloured matrix of quartz and tourmaline. Fragments range in size from granules (4 mm) to cobbles (256 mm). Larger fragments are angular to subangular. Following Krumbein (1963, p. 111, Appendix I), these larger fragments have an average sphericity of 0.5 and a roundness of 0.1. The granules are often quite rounded and commonly surround larger fragments. Feldspar phenocrysts within the fragments have been altered to sericite. Box works after sulphides within the fragments are commonly void. Where the breccia is made up of smaller grain size fraction, the grains do not touch and are completely surrounded by the quartz-tourmaline matrix. Where the fragments are of cobble size, they are always touching each other and are poorly cemented.

The matrix is composed of fine-grained acicular green tourmaline (schorlite), quartz and possibly apatite. Where there is abundant matrix, vugs make up 5% of it. The larger vugs (4 - 8 mm), are oftened coated with jarosite and may represent box works after sulphides. Smaller (1 mm) unlined vugs probably represent gas vesicles.

Plate 14. Tourmaline breccia. Altered fragments are rhyodacite porphyry.

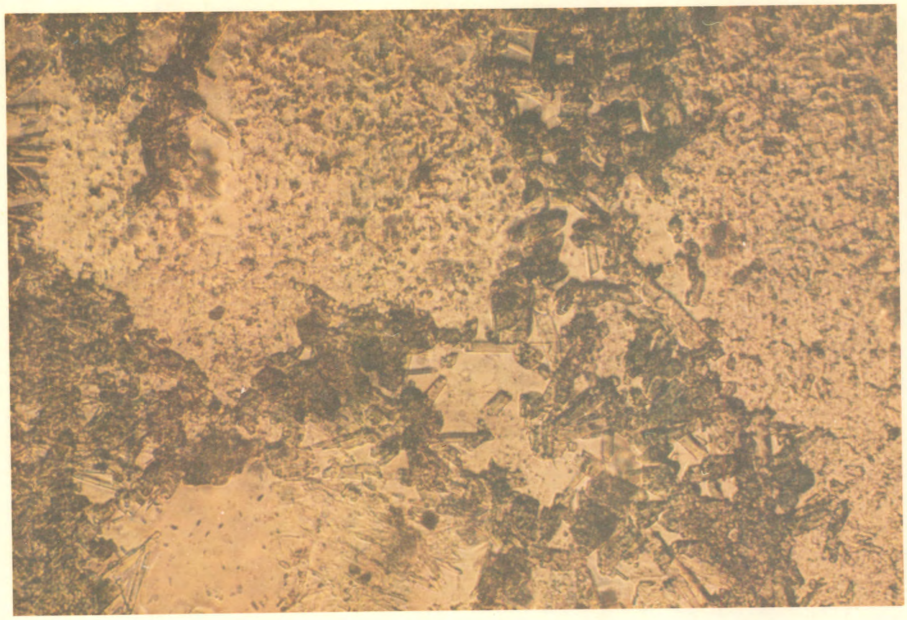


Plate 15. Photomicrograph of subhedral tourmaline (green) surrounding altered rock fragments (white). X 40

Stratigraphy and Interpretation

The rock units in the preceeding section have been described in a probable order of decreasing age.

The Yukon group forms the basement in the Mount Nansen area. The group is composed wholly of metamorphics. Hornblende gneiss and metaquartzite is exposed in a window south of Discovery Creek. These rocks are of sedimentary origin although the group also contains members of possible igneous or volcanic origin. Bostock (1936) places the Yukon group in age from Precambrian to pre-Triassic.

Following the polyphase deformation of the Yukon group, the Mount Nansen volcanics were extruded. In the Mount Nansen area the volcanics form a thick cover of andesite flow breccia and porphyritic andesite. The breccias were formed early in this stage of volcanism as they sometimes contain fragments of metamorphics along with more typical, porphyritic andesite fragments. The petrography of a hornblende monzonite porphyry sill and dykes suggest this unit is genetically related to the volcanics. Quartz is almost completely absent in this rock. The sill and dykes are found at the northwest corner of the map and may represent a feeder-dyke system. The Mount Nansen group has been restricted to late Jurassic-early Cretaceous by Bostock (1936). Cairnes (1915) found evidence that some of the volcanics were younger than Cretaceous sediments.

The two groups are intruded by a batholith of hypersthene-quartz diorite and a more areally extensive unit of quartz monzonite. The hypersthene-quartz diorite is found as small, irregular bodies peripheral to the quartz monzonite. Volumetrically, quartz, hornblende and biotite vary locally within the quartz monzonite unit. Several float samples show the diorite unit has been intruded by the quartz-monzonite, presumably at a lower tectonic level. However, these two units are probably comagmatic. K-Ar dating of granodiorites from the batholith, has given a mid-Cretaceous age of 97 $\pm$ 2 my. (Findlay, 1969). The samples were obtained 65 miles northwest of the Mount Nansen area. This batholith can be correlated with the Coast Range intrusives.

The youngest rocks in the area are an acid, porphyritic suite with spatially associated rhyolites. Three petrographically distinct porphyries form a northwest trending elongate stock which is spatially related to the batholithic rocks. This relation again suggests comagmatism. A biotite-quartz monzonite phase and a quartz-monzonite porphyry phase are exposed peripheral to a central core zone of rhyodacite porphyry. The biotite-quartz monzonite is characterized by abundant, regularly distributed biotite, minor plagioclase phenocrysts and lack of quartz phenocrysts, which are ubiquitous to both the other porphyry units. The quartz-monzonite porphyry is distinguished by large resorbed quartz phenocrysts, plagioclase phenocrysts, a light cream groundmass and only minor mafics. The rhyodacite porphyry is characterized by resorbed quartz phenocrysts, plagioclase phenocrysts and large orthoclase phenocrysts. The matrix of this rock is light grey, contains less potash feldspar and is finer-grained than the presumably earlier phases. The rhyodacite porphyry probably was intruded later and at a higher tectonic level than both other phases. This hypothesis is consistent with grain-size comparison and K-Ar age dating of a similar stock at the Casino deposit. Here, a fine-grained porphyritic dacite yielded a Palaeocene age of 69 $\pm$ 3 my., while a late-Cretaceous age of 71 $\pm$ 3 my. was recorded for a coarser-grained variety (Godwin, 1970). These relative ages may be significant with regards to a quickly rising magma.

Quartz-feldspar porphyry dykes are mineralogically related to this period of intrusion. They are characterized by quartz and plagioclase phenocrysts in a microcrystalline matrix consisting almost totally of potash feldspar. The dykes trend north and northeast, and are often found alongside dykes of hornblende monzonite porphyry, possibly following the same structural weaknesses. The quartz-feldspar porphyry dykes may represent radial dykes to the porphyry intrusions.

Outliers of rhyolite and rhyolite tuff crop out within the area. They are probably related to the hypabyssal acid suite described above. There is a suggestion of rhyolite porphyry interbedded with Mount Nansen andesites at the south-west edge of the map. Here andesite may overlay rhyolite. The rhyolite unit has been placed in the Tertiary by both Cairnes (1915) and Bostock (1936). Hence Mount Nansen volcanism may have also extended into Tertiary time.

At least one period of hydrothermal activity and associated brecciation has occurred after the emplacement of the stock. Two zones of breccia consisting of rhyodacite porphyry fragments cemented with a quartz-tourmaline matrix and one breccia of rhyodacite and Mount Nansen group fragments cemented with a siliceous matrix crop out in the area. All the breccias are associated with lineaments. The two tourmaline breccias appear to be within the boundaries of the composite porphyry stock. The brecciated body containing both porphyry and Mount Nansen group lava fragments is probably a nearer surface expression of the same process that formed the tourmaline breccias.

Several models for the formation of breccia zones have been advanced in recent years, primarily because of their association with economic mineralization. Of 27 porphyry copper deposits studied by Lowell and Guilbert (1970), breccia pipes were present in 20 and mineralized in 18 deposits.

Sillitoe and Sawkins (1971) in a recent paper have postulated, fluid corrosion and subsequent collapse as a mode of formation for many of the Chilean tourmalinized breccia pipes. Fluid inclusion studies indicated pipe genesis occurred 2 - 3 km. below the then existing surface. The fine-grained matrix of the fragments within the Mount Nansen tourmaline breccias may indicate a higher level of formation.

Collapse consequent on release of supporting magmatic pressure has been advanced by Perry (1961) as another method of breccia formation. The relatively small size of fragments found in the tourmaline breccia of the Mount Nansen area is probably not compatible with this hypothesis.

The tourmaline breccias are not believed to be fault breccias although lineaments are associated with them. The absence of fragments showing shearing, the equidimensional plan of exposure and finer fragments associated with larger fragments are not characteristic of fault breccias.

White, et al (1957) have hypothesized that the tourmaline breccias of the Highland Valley area are caused by explosion in the lower part of volcanic structures. They propose that the pressure of volatiles in a cupola exceeds the confining pressure, and that the resultant explosions fragment the rock. Gases or supercritical fluids escape through breccias, locally entraining and redistributing fine matrix material, but not apparently rounding the larger fragments.

In the Mount Nansen area extensive hydrothermal alteration and outliers of rhyolite tuff that are associated with the hypabyssal porphyry intrusion, suggest this explosive mechanism as being the most favourable for the development of the breccias. Hydrothermal fluids streamed through these newly formed breccia bodies and adjacent fissures causing the alteration mineral zoning that will be described next.

ROCK ALTERATION

Foreword

For an alteration zoning study it is necessary to obtain an assemblage of alteration minerals from each sample. Some alteration minerals; such as clay, can occur in several zones and are not diagnostic. By identifying a group of minerals with the same stability relationships, a zone can be determined. The rocks within a given zone can be interpreted as having undergone the same chemical changes.

Surface rock alteration in the Mount Nansen area is pervasive and a zone will imply a scale of several hundreds of feet.

Alteration minerals were identified by preparing 33 X-ray diffraction traces of feldspar phenocrysts, examination of 40 thin sections and field mapping.

For all X-ray diffraction traces, CuKα radiation was used. First order 7.16-7.17 Å peaks were taken to represent a kaolinite group mineral while first order peaks of 9.98-10.1 Å were thought to represent muscovite basal spacings.

Three samples showing kaolinite group mineral peaks were heat treated to test the validity of this assumption. Slides of samples D-97, 2-300, and 2-360 were heated for 8 hours at a temperature of 550°C. The presence of a kaolinite group mineral was confirmed in all three samples by the disappearance of the 7 Å peak. The muscovite peaks were unaffected. Kaolinite will be used to mean a kaolinite group mineral for the remainder of this discussion.

Alteration Types

Several types of rock alteration have probably occurred in the Mount Nansen area. They are deuteric, supergene and hypogene. The term deuteric alteration implies alteration in an igneous rock produced during the later stages of, and as a direct consequence of, the consolidation of magma or lava. The term discriminates such alterations from the more strictly secondary changes due to a later or hypogene period of alteration. Hypogene alteration is caused by an influx of high temperature solutions into crystallized rock usually at depth. The term supergene alteration denotes rock alteration caused by weathering and related near surface processes involving solutions of nearby surficial origin. Acid solutions derived from the oxidation of iron sulphides play an important role in causing supergene alteration.

The alteration minerals and mineral assemblages formed by these various processes are often the same. Distinction between these alteration types is not easy (Rose, 1970; Meyer and Hemley, 1967; Schwartz, 1956) and, in fact, is impossible in the Mount Nansen area at this stage of surface study. However, some qualitative assumptions can be made about the extent of the three types. The discussion to follow is concerned mainly with hypogene alteration but the effects of deuteric and supergene alteration will be mentioned where involved.

Alteration Zoning

Studies of mineralogical zoning suggest there are at least four and probably five hypogene alteration assemblages discernable in and around porphyry copper deposits. The terms potassic, advanced argillic, phyllic, argillic and propylitic have been used by Meyer and Hemley (1967) and by Meyer, Shea and Goddard (1968) to describe various alteration zones characterized by a particular mineral assemblage.

Potassic zones commonly include the assemblage potash feldspar, biotite, magnetite and anhydrite. An advanced argillic zone is distinguished by the assemblage, quartz, sericite, tourmaline, kaolinite, pyrophyllite and dickite. Phyllic zones are distinguished by the mineral assemblage, quartz, sericite and pyrite. Quartz, kaolinite and montmorillonite group minerals are predominant in the argillic zone. Finally, propylitic zones are characterized by the assemblage, chlorite, epidote, carbonate and albite. These zones have been found to grade into each other. Commonly the potassic or advanced argillic zone is found closest to the heat and solution source. Phyllic, argillic and propylitic assemblages are found in that order out from the more intensely altered core zone. The repeated appearance of these specific mineral assemblages suggest repetition of similar physical-chemical conditions especially when coupled with the fact that the altered parent rock of most porphyry coppers is of the same composition (Creasey, 1966).

Four surface alteration zones with characteristic mineral assemblages were separated in the thesis area. These zones are named advanced argillic, phyllic, argillic and propylitic. Phyllic and argillic alteration is by far the most widespread. The hydrothermal system was centered in the middle of the composite porphyry stock. Two quartz-tourmaline breccias, and several other silicified domal structures appear to be the centres of hydrothermal emanations. Advanced argillic and phyllic alteration are characteristic of these areas. Less intense, argillic and propylitic assemblages can be found in roughly concentric zones around these centres.

The main parameters that have controlled the alteration pattern are believed to be:

1) post-alteration faulting
2) changes in wall rock composition
3) frequency of guiding fractures
4) progressive changes in composition of hydrothermal fluids from source outwards

Post-alteration faulting has occurred along the Wheeler-Fault. An intense phyllic zone exposed south of the Fault ends abruptly against it. North of the Fault rocks are only slightly altered to a propylitic assemblage. The extension of the phyllic zone could not be located. It may have been offset left laterally to the topographically low Summit Creek area.

Rock composition has only affected the ring-like pattern where the hydrothermal fluids have passed through basic, volcanic rocks. For example, at the headwaters of Courtland Creek, a phyllic alteration of porphyry intrusives changes immediately into a propylitic assemblage at the contact with andesites. Fractures within the andesite are filled with epidote. The similarity in chemical composition of the early-Tertiary porphyry intrusives and the surrounding quartz monzonite batholithic rocks has not affected a concentric zonal pattern of alteration minerals.

The frequency of guiding fractures for channelling the hydrothermal fluids has played an important role in localizing hydrothermal activity. At least four central or core zones exist where hydrothermal fluids have been channelled in larger amounts by fractured and brecciated areas, then penetrated equivalent volumes of rock elsewhere. The two breccia pipes have an advanced argillic mineral assemblage and are surrounded successively by phyllic and argillic halos. At least two other core areas exist. These are areas of intense phyllic alteration surrounded by argillic and propylitic assemblages. All the hydrothermal alteration centres are characterized by silica in excess of what could be expected from the breakdown of silicates. These silicified areas are topographically anomalous. Centres of hydrothermal activity are shown on the map (Appendix 3).

Of course, the main parameter of mineral zoning must be the changing composition of the altering fluids. Zones reflect the extent of hydrolitic decomposition of the silicate host rocks by the hydrothermal fluids (Hemley and Jones, 1964). This will be discussed in the section on chemistry.

Description of Alteration Zones

Advanced Argillic

Within the Mount Nansen stock, the advanced argillic zone is characterized by the mineral assemblage; quartz, tourmaline, sericite, minor kaolinite and possibly apatite. Only the tourmaline breccia bodies are found to have this assemblage. Tourmaline is the only mineral that distinguishes this group from phyllic alteration. It is possible that more than one period of hydrothermal alteration has occurred to produce this advanced argillic assemblage.

The matrix of the breccia is composed solely of quartz, tourmaline and possibly minor apatite. The rhyodacite porphyry fragments have kept their original porphyritic texture. Feldspar phenocrysts within the fragments have been pseudomorphically replaced by quartz and sericite. Quartz phenocrysts within the fragments remain unaltered. The groundmass of the fragments is a mixture of quartz, sericite and minor kaolinite.

Sulphides may have also been included in this assemblage. Jarosite thinly coats most of the cavities in the breccia. Jarosite will precipitate from the oxidation of iron sulphides in a potassium rich, acidic environment (McKinstry, 1948, p. 255). The potassium is available from the sericite gangue.

Phyllic Zone

The phyllic zone is characterized by the minerals quartz, sericite, pyrite and minor kaolinite. This assemblage occurs outward from the advanced argillic zone and, as was mentioned earlier, occurs as alteration core zones itself.

Sericite, quartz, and kaolinite commonly replace the feldspars and matrix of the rock pseudomorphically so that the original texture remains (Plate 16).

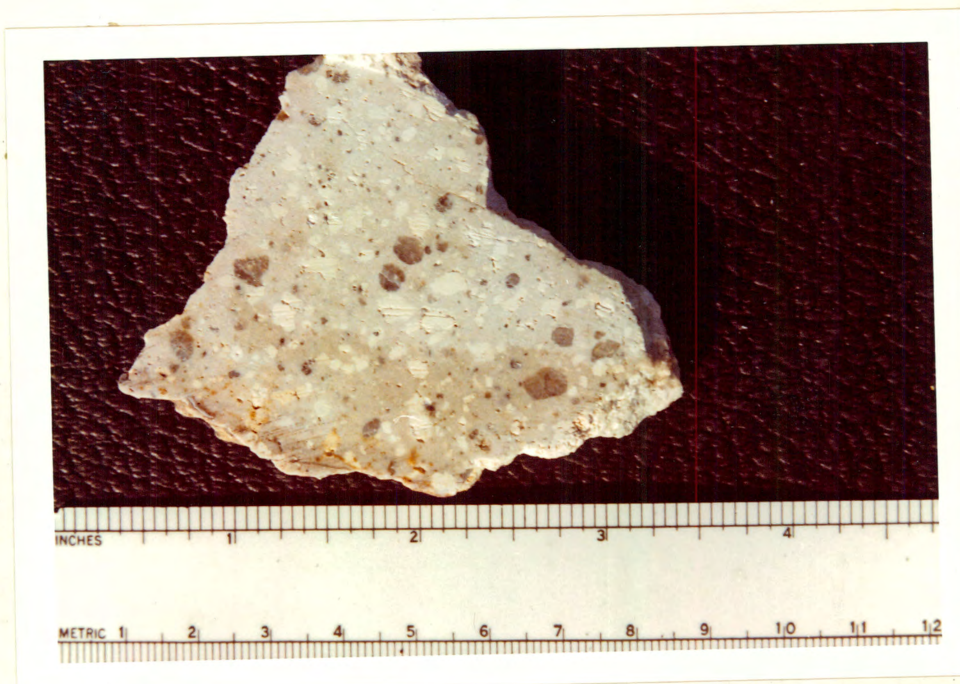


Plate 16. Quartz and sericite (white) has replaced feldspars of rhyodacite porphyry. Porphyritic texture remains.

No mafics are left in this zone. Some rocks within the more intense areas of phyllic alteration have been altered to a fine grain mass of quartz and sericite. In these areas only quartz phenocrysts remain as evidence of the rock's original porphyritic texture (Plate 17).

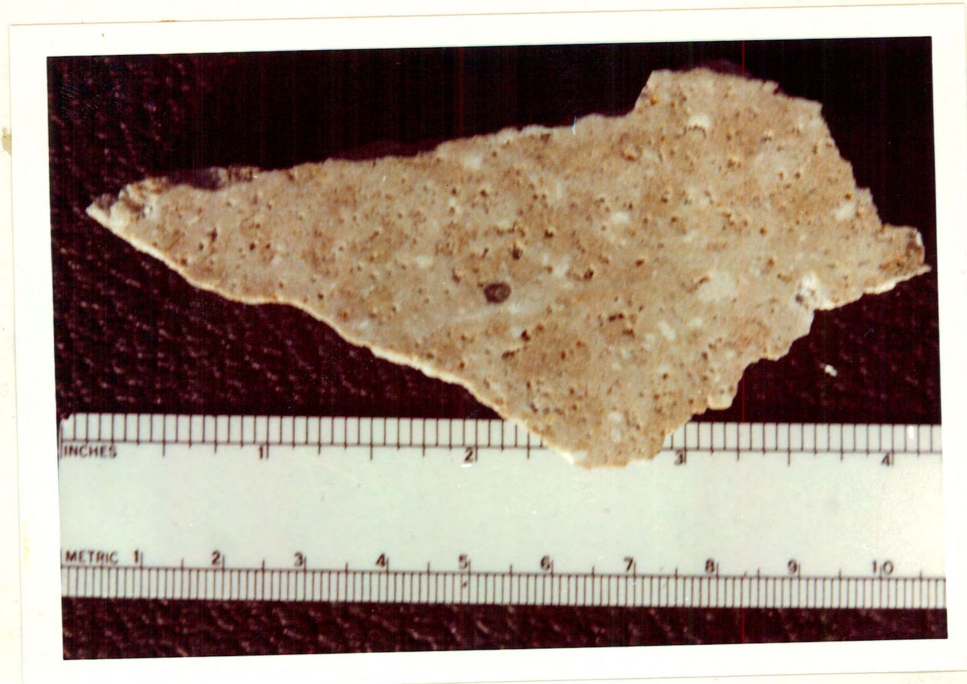


Plate 17. Intense phyllic alteration. One quartz phenocryst remains.

Where phyllic alteration of the quartz monzonite batholithic rocks has occurred, its equigranular texture commonly remains (Plate 18).

Plate 18. Phyllic alteration of a quartz monzonite rock. Equigranular texture remains.

The extreme porosity of the rocks that have undergone this type of alteration has favoured the leaching out of all iron sulphides. Most of the vugs left by the sulphides are void of limonite. Iron oxide has been transported out from these vugs into the surrounding rock, commonly precipitating as potassium-rich jarosite. The precipitation of jarosite gives the surface rock of the phyllic zone a yellow-brown colouration (Plate 19).

Plate 19. Sulphides are completely leached from rock. Transported Fe^{++} has precipitated as jarosite, staining rock.

There are several problems in defining an outside limit to the phyllic zone or conversely, an inside limit to the argillic zone. Most authors that have described porphyry-copper alteration zoning suggest sericite is of hypogene origin. Rose (1970) questions this assumption by pointing out, there is an abrupt change from sericite to biotite at the base of the leached capping at Safford, Arizona. Hemley and Jones (1964) indicate that sericite is stable at moderately high $\frac{K^+}{H^+}$ ratios (Figure 3), at low temperatures; an environment consistent with high pH. The extremely low pH found in most supergene alteration zones argues against the important development of supergene sericite. Since most silicates including sericite will alter to kaolinite under supergene conditions, sericite was identified as hypogene in the Mount Nansen stock. This assumption is reinforced by the fact that x-ray diffraction traces showed sharp sericite peaks; indicative of an ordered crystal structure. Disordered crystal structures are common with minerals of a supergene origin.

Secondly, providing the sericite is hypogene, how extensively has it been replaced by kaolinite? A supergene origin for clay is now widely accepted. Hemley and Jones (1964) state that under supergene conditions most silicate minerals will tend to alter directly and completely to kaolinite. Garrels and Howard (1959) have shown that at a temperature of 25°C and 1 atmosphere pressure, high H^+ promotes the replacement of mica and potash feldspar to clay. These conditions are exactly those found in the near surface oxidized zones of porphyry copper deposits.

Widespread supergene kaolinization of silicates is suspected in the Mount Nansen area. All the feldspar phenocrysts of porphyritic rhyolite for example, have been completely replaced by kaolinite. The rhyolites crop out several miles away from centres of hydrothermal activity.

Economically, the quartz-sericite-pyrite or phyllic zone is of great importance and thus its delineation is also of importance. Twenty-five of twenty-seven porphyry copper deposits of the southwestern United States, studied by Lowell and Guilbert (1970, p. 401), have a quartz-sericite zone.

This zone is found to be the chief ore bearer in most deposits. Sericite must be used as the key indicator for a phyllic alteration zone. Feldspar phenocrysts with greater than 10% sericite development were considered to exhibit phyllic alteration in the Mount Nansen stock alteration pattern. The other 90% may or may not be kaolinite. However, it should be pointed out again that most of the phyllic zone is composed of quartz and sericite that has completely replaced the feldspars. Where phyllic alteration has been intense, the rocks are altered to a fine grain mass of quartz and sericite.

Argillic Zone

The argillic zone is characterized by the alteration assemblage kaolinite, quartz and minor sericite. It occurs as a halo around the phyllic zone and is very widespread.

Rocks within this zone always retain their parent texture. Feldspar phenocrysts are usually completely replaced by kaolinite and quartz. The phenocrysts are bleached white and are extremely soft. The matrix is also commonly bleached and softened to a lesser degree. Quartz phenocrysts always remain unaltered. Limonitic staining, commonly goethite, is found on weathered surfaces of rock fragments. Sulphides are typically completely leached out and only void crystal outlines remain.

Unlike many porphyry copper environments there is no evidence at surface of an outer montmorillonite sub-zone.

None of the feldspar phenocrysts x-rayed showed a trace of montmorillonite. If there was an argillic montmorillonite-sub-zone, it is likely that it has been overprinted by supergene kaolinization. Several descriptions of argillic zones in porphyry copper deposits indicate potash feldspar phenocrysts are commonly less altered than plagioclase. In the argillic zone of the Mount Nansen stock all feldspars are almost completely kaolinized.

The outer limit of the argillic zone is the first appearance of mafic minerals; commonly books of biotite that have been completely chloritized.

The significance of the argillic assemblage as a hypogene alteration zone is not known. The possibility that much of the kaolinite in this zone, the phyllic zone and the advance argillic zone, has been produced by supergene alteration is great. However, x-ray traces showed the mineral assemblage quartz-sericite-kaolinite for feldspar phenocrysts sampled from a percussion drill hole (CP-2) from surface to a bottom depth of 360 feet. Kaolinite at 360 feet may indicate that at least some of the clay has a hydrothermal origin.

Propylitic Zone

The propylitic alteration zone is characterized by the minerals, epidote, clinozoisite, albite, chlorite, leucoxene, carbonate, pyrite, and minor sericite and clay.

Propylitic alteration is a fringe or outer zone and grades from a rock that has epidote and carbonate fracture fillings and bright green chloritized mafics to rocks that look fresh in the field. Thin section examination showed all rocks outside of the argillic alteration zone to be propylitized to some extent. Rocks several miles away from the intensely altered stock showed propylitic assemblages. Rocks within a 1,000 feet of the argillic zone showed all mafics to have been replaced by aggregates of chlorite, leucoxene, epidote and carbonate or uncommonly biotite or actinolite. Hornblende and biotite were probably the original mafic minerals. Plagioclase appearing fresh in hand specimen shows alteration in thin section. Calcic zones are commonly preferentially altered whether they comprise the core of normally zoned crystals or intermediate rings where oscillatory zoning has occurred. Minerals replacing the plagioclase are an albite, epidote, carbonate mixture or uncommonly clay. Sericite sometimes flecks plagioclase. Potash feldspar is commonly unaltered.

Unoxidized pyrite is common in this zone. Pyrite sometimes makes up 10% of the rock's total volume. When pyrite is oxidized, in this propylitic zone, a deep reddish-brown hematitic limonite forms on weathered surfaces. Small amounts of hematite were noticed along the banks of Eva Creek. Most of the propylitic zone is in quartz-monzonite batholithic rocks.

The widespread occurrence of the propylitic assemblage indicates that some of these minerals were formed by deuteric or supergene processes. Where epidote and calcite occur as fracture fillings to any extent, it is probably safe to conclude a hydrothermal origin for that particular propylitic alteration. This fracture filling form of alteration does occur just outside the argillic zone. Hemley and Jones (1964) indicate that it is almost impossible to distinguish between deuteric alteration or igneous bodies, which is characteristically propylitic and a later incipient propylitic alteration. For this reason only the inner limit of propylitic alteration is shown in the alteration pattern of the Mount Nansen area.

Chemistry

Four alteration zones have been recognized in the Mount Nansen area. The four zones have been named: advanced argillic, phyllic, argillic and propylitic. The advanced argillic and phyllic zones are core areas, surrounded successively by argillic and propylitic zones. Each zone is characterized by a specific mineral assemblage. These differing mineral assemblages and their zones reflect differing degrees of hydrolytic decomposition of the silicate host rocks. More specifically, they reflect the results of reaction of silicate rocks with solutions in which $\frac{\text{cation}}{H^+}$ activity ratios were low, intermediate or high (Hemley, 1964).

Activity can be thought of as concentration, modified by the effects of hydrothermal fluids and dissolved substances.

Hydrolysis may be defined as a decomposition reaction with hydrothermal fluids in which either H^+ or OH^- ions are consumed by silicate minerals which then must release to solution an amount of cation, chemically equivalent to the quantity of H^+ consumed. Hydrolysis then, is simply hydrogen metasomatism (Hemley, 1964).

The propylitic zone is the fringe zone to areas where more advanced type hydrothermal alteration has occurred. The mineral assemblage includes chlorite, albite, epidote, carbonate, leucoxene and minor sericite. Very little hydrolysis has taken place in this zone. Low cation H^+ activity ratios are expected. Most of the minerals have formed by the hydration (addition of H_2O) of biotite and hornblende. CO_2 has also been added to form carbonates. The K^+ released by the chloritization of biotite, before extensive decomposition of feldspars, probably produced the small amounts of sericite. This hydrolytic reaction may be represented by the equation (Meyer, 1967):

$$\underset{\text{biotite}}{2K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + 4H^+ \rightarrow \underset{\text{chlorite}}{Al(Mg,Fe)_5AlSi_3O_{10}(OH)_8} + (Mg,Fe)^{+2} + 2K^+ + 3SiO_2$$

The equation shows the low $\frac{\text{cation}}{H^+}$ activity ratio characteristic of propylitic alteration. This propylitic mineral assemblage can also be produced by deuteric and supergene alteration.

The argillic zone is indicative of intermediate hydrolytic decomposition of silicate minerals. Kaolinite and quartz are the prominent alteration minerals of this zone. Kaolinite is unstable above 400°C. setting a maximum temperature limit for argillic alteration (Creasey, 1966). Potash feldspar and plagioclase have been completely replaced by kaolinite and quartz within much of this zone. Mafics are absent. The boundaries between the argillic and propylitic, and the argillic and phyllic zones are gradational over several hundred feet. The kaolinization of plagioclase, represented by the equation (Hemley, 1964):

$$\underset{\text{andesine}}{Na_2CaAl_4Si_8O_{24}} + 4H^+ + 2H_2O \rightarrow \underset{\text{kaolinite}}{2Al_2Si_2O_5(OH)_4} + 4SiO_2 + 2Na^+ + Ca^{+2}$$

typifies intermediate $\frac{\text{cation}}{H^+}$ activity ratios of the hydrothermal solutions and the resulting hydrolytic reactions expected in the argillic zone.

The total replacement of potash feldspar by kaolinite in this zone may indicate extensive supergene formation of kaolinite. Figure 3 adopted from Hemley and Jones (1964) shows the relative stabilities of kaolinite, muscovite and potash feldspar. Potash feldspar should be stable under the intermediate hydrolysis expected in the argillic zone. The formation of kaolinite is seen to be favoured by low temperatures and low alkali ion/H^+ ratios. This is consistent with the acidic environment of supergene alteration. Rapid removal of dissolved cations in a supergene leaching environment would hinder the crystallization of intermediate products, such as, sericite. Thus, in a low temperature and low alkali ion/H^+ environment, most silicates would tend to alter directly and completely to kaolinite (Hemley, 1964). Hypogene sericite may also have been replaced by supergene kaolinite. The following reaction would exemplify this process:-

$$2KAl_3Si_3O_{10}(OH)_2 + 2H^+ + 3H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2K^+$$

muscovite kaolinite

The phyllic and advanced argillic alteration zones are core zones. Hydrothermal fluids circulating in these areas had a high $\frac{\text{cation}}{H^+}$ activity ratio. Tourmaline differentiates the advance argillic zone from the phyllic zone. The introduction of boron may represent a separate period of hydrothermal activity. Sericite, quartz, and minor clay are common to both. The upper temperature limit of quartz-sericite alteration is about 625°C (Creasey, 1966). In these alteration zones quartz is present in greater amounts than could be expected from the breakdown of rock-forming silicates. Pyrite was probably included in this alteration mineral assemblage. However, under supergene attack, iron sulphides have completely altered to jarosite and goethite.

The alteration process of these zones is expressed dominantly by the decomposition of plagioclase and orthoclase and is illustrated by the equations:

$$3Na_2CaAl_4Si_8O_{24} + 8H^+ + 4K^+ \rightarrow 4KAl_3Si_3O_{10}(OH)_2 + 6Na^+ + 3Ca^{+2}$$

andesine sericite

$$+ 12SiO_2$$

quartz

$$3KAlSi_3O_8 + 2H^+ \rightarrow KAl_2AlSi_3O_{10}(OH)_2 + 2K^+ + 6SiO_2$$

orthoclase sericite quartz

System K_2O-Al_2O_3-SiO_2-H_2O:

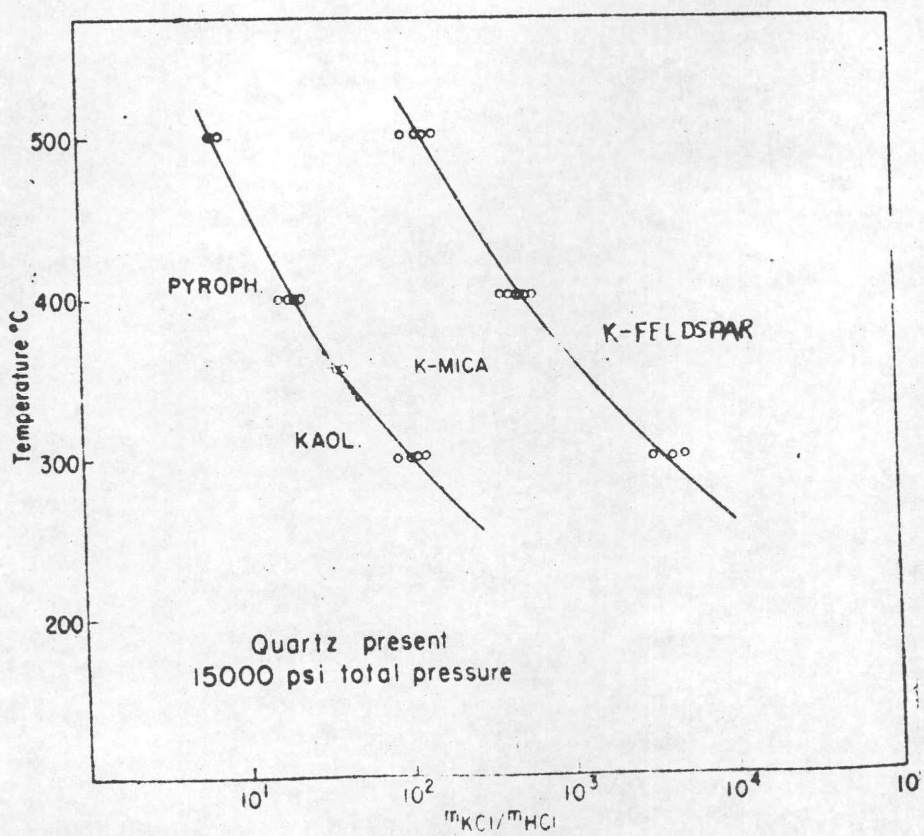


Figure 3. Reaction curves for the system K_2O-Al_2O_3-SiO_2-H_2O. The dot-dashed line indicates experimental decomposition temperature of kaolinite in 0.5m KCl solution. (Hemley and Jones, 1964)

High temperature and high $\frac{cation}{H^+}$ ratios of the altering fluids will cause the above reactions to proceed (Figure 3). Potassium to produce sericite from plagioclase can be derived from the hydrothermal fluids or as shown above by the breakdown of orthoclase. Minor kaolinite is probably derived from supergene alteration of sericite.

INTERPRETATION

Advanced argillic, phyllic, argillic and propylitic alteration zones have been recognized, with the hydrothermal system centered in the early-Tertiary porphyry stock. Pre-alteration and post-alteration fracturing and faulting has occurred. Pre-alteration fractures have guided the rock altering fluids into at least four core areas. Core zones are typified by mineral assemblages characteristic of advanced argillic and phyllic alteration. The introduction of boron rich solutions with subsequent crystallization of tourmaline may represent a separate period of hydrothermal alteration. The effect of this period of hydrothermal activity would superimpose itself over an existing pattern by increasing the intensity of alteration. This effect is suggested by the alteration pattern found at the headwaters of Courtland Creek. An inferred continuation of the Wheeler Fault has not offset the alteration pattern around an advanced argillic core zone. However, the Wheeler Fault does appear to offset alteration patterns to the east which are characterized by phyllic core zones. Tourmalinization then may have been post-Wheeler Fault while phyllic alteration core zones are probably pre-Wheeler Fault. Conversely the inferred continuation of the fault may not exist. The continuation of the alteration pattern north of the Wheeler Fault could not be located. A left-lateral displacement is suggested by one inferred fracture offset.

Surrounding the core areas are irregular halos of argillic and propylitic alteration mineral assemblages.

Figure 4 shows the mineral assemblages characteristic of each zone representing an outward decrease in temperature or $\frac{K^+}{H^+}$ or both, of the altering fluids. Some of the pervasive kaolinization may have been produced by supergene alteration. However, kaolinite has been identified at a depth of 360 feet below surface suggesting some kaolinite may also be hypogene.

Unlike many alteration zones found in porphyry environments a potassic core zone, characterized by the mineral assemblage of secondary K-feldspar and biotite, was not found. The explanation for this lack of identifiable potassic alteration may be due to several factors. Listed in increasing order of probability, these factors are:

1) eradication of secondary K-feldspar by supergene kaolinization

2) lack of high, temperature and $\frac{K^+}{H^+}$ ratios in the altering fluids

3) lack of sufficient erosion to expose the potassic assemblage

The lack of sufficient erosion to expose the potassic assemblage is favoured for several reasons. These are:

1) absence of extensive glacial erosion

2) breccia zones probably represent high level hydrothermal activity

3) the extensive development of sericite argues for high $\frac{K^+}{H^+}$ ratios in the altering fluids

4) the overall zonal alteration pattern is characteristic of porphyry deposits with potassic alteration core zones

This level of exposure is diagramatically presented in Figure 4.

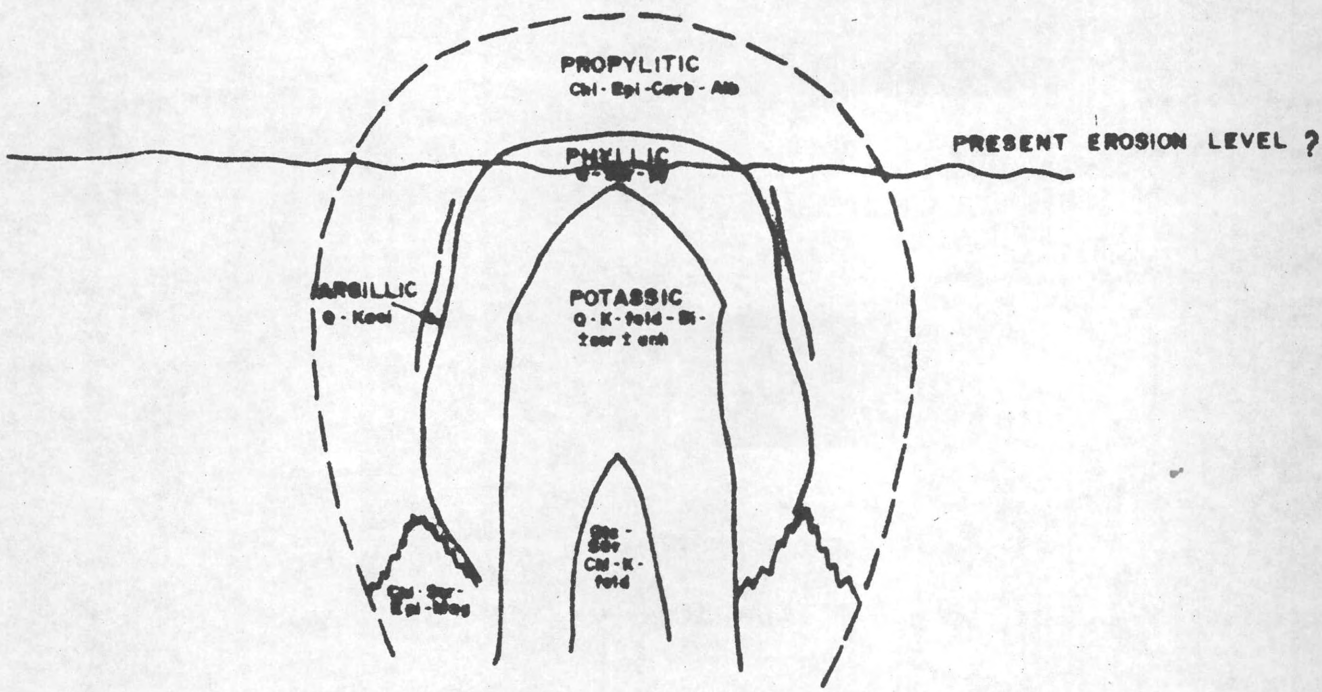


Figure 4. Schematic drawing of alteration zones in porphyry ore deposits. (After Lowell and Guilbert, 1970)

BIBLIOGRAPHY

Abbot, G., 1971 — The geology of the Williams Creek copper prospect; unpublished B.Sc. thesis, University of British Columbia.

Bostock, H.S., 1936 — Carmacks district, Yukon; Geological Surv., Can., Mem. 189.

1966 — Notes on glaciation in central Yukon Territory; Geol. Surv., Can., Paper 65-36.

Cairnes, D.D., 1914 — Exploration in southwestern Yukon; Geol. Surv., Can., Mem. 284, pp. 354-380.

1917 — Investigations and mapping in Yukon Territory; Geol. Surv., Can., Mem. 284, p. 442.

Creasey, S.C., 1966 — Hydrothermal alteration; in Geology of Porphyry Copper Deposits Southwestern North America, ed. S.R. Titley and C.L. Hicks, Tucson, University of Arizona Press, pp. 51-75.

Findlay, D.C., 1969 — The mineral industry of Yukon Territory and southwestern District of Mackenzie; Geol. Surv., Can., Paper 69-55.

Garrels, R.M. and Howard, P.F., 1959 — Reaction of feldspar and mica with water at low temperature and pressure; in Clays and Clay Minerals, ed. A. Swineford, Internat. Ser. Mons. Earth Science, Vol. 2, pp. 68-88.

Godwin, C.I. and Phillips, M.P., 1970 — Geology and Rotary Drilling at the Casino Deposit, Yukon Territory; paper presented to C.I.M.M. symposium at Kamloops, 1970.

Hemley, J.J. and Jones, W.R., 1964 — Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism; Econ. Geol., Vol. 59, pp. 538-569.

Hughes, O.L., Campbell, R.B., Muller, J.E. and Wheeler, J.O., 1969 Glacial limits and flow patterns, Yukon Territory, south of 65 degrees north latitude; Geol. Surv., Can., Paper 68-34.

Krumbein, W.C. and Sloss, L.L. 1963 Stratigraphy and Sedimentation; W.H. Freeman and Comp., San Francisco, p. 111.

Lowell, D.J. and Guilbert, J.M. 1970 Lateral and vertical alteration - mineralization zoning in Porphyry Ore deposits; Econ. Geol., Vol. 65, No. 4 pp. 373-408.

McKinstry, H.E. 1948 Mineralogical guides; in Mining Geology, ed. N.E. Hinds, New Jersey, Prentice Hall, Inc., pp. 233-276.

Meyer, C. and Hemley, J.J. 1967 Wall rock alteration; in Geochemistry of Hydrothermal Ore Deposits, ed. H.L. Barnes, New York, Holt, Rhinhart and Winston, pp. 166-235.

Meyer, C., Shea, E.P., and Goddard, C.C. 1968 Ore deposits at Butte, Montana; in Ore Deposits of the United States, 1933-1967, ed. J.D. Ridge; New York, Am. Inst. Min. Eng., pp. 1373-1416.

Perry, V.D., 1961 The significance of mineralized breccia pipes; Min. Eng. Trans., Vol. 13, No. 4, pp. 366-476.

Rose, A.W., 1970 Zonal relations of wall rock alteration and sulphide distribution at Porphyry Copper Deposits; Econ. Geol., Vol. 65, pp. 920-936.

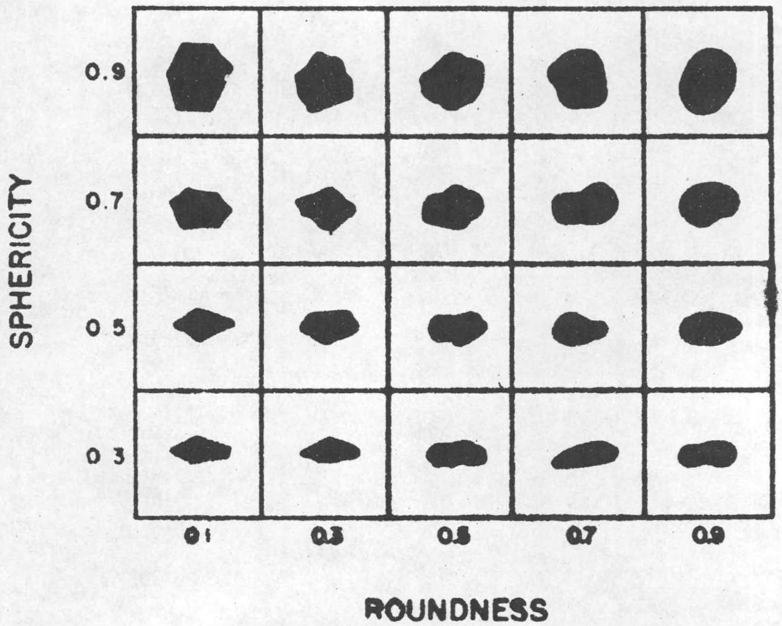
Schwartz, G.M. 1956 Argillic alteration and ore deposits; Econ. Geol., Vol. 51, No. 5, pp. 407-413.

Sillitoe, R.H. and Sawkins, F.J. 1971 Geologic, mineralogic and fluid inclusion studies relative to the origin of copper-bearing tourmaline breccia pipes, Chile; Econ. Geol., Vol. 66, pp. 1028-1041.

Stringham, B., 1966 Igneous rock types and host rocks associated with porphyry copper deposits; in Geology of the Porphyry Copper Deposits Southwestern North America, ed. S.R. Titley and C.L. Hicks, Tucson, University of Arizona Press, pp. 35-40.

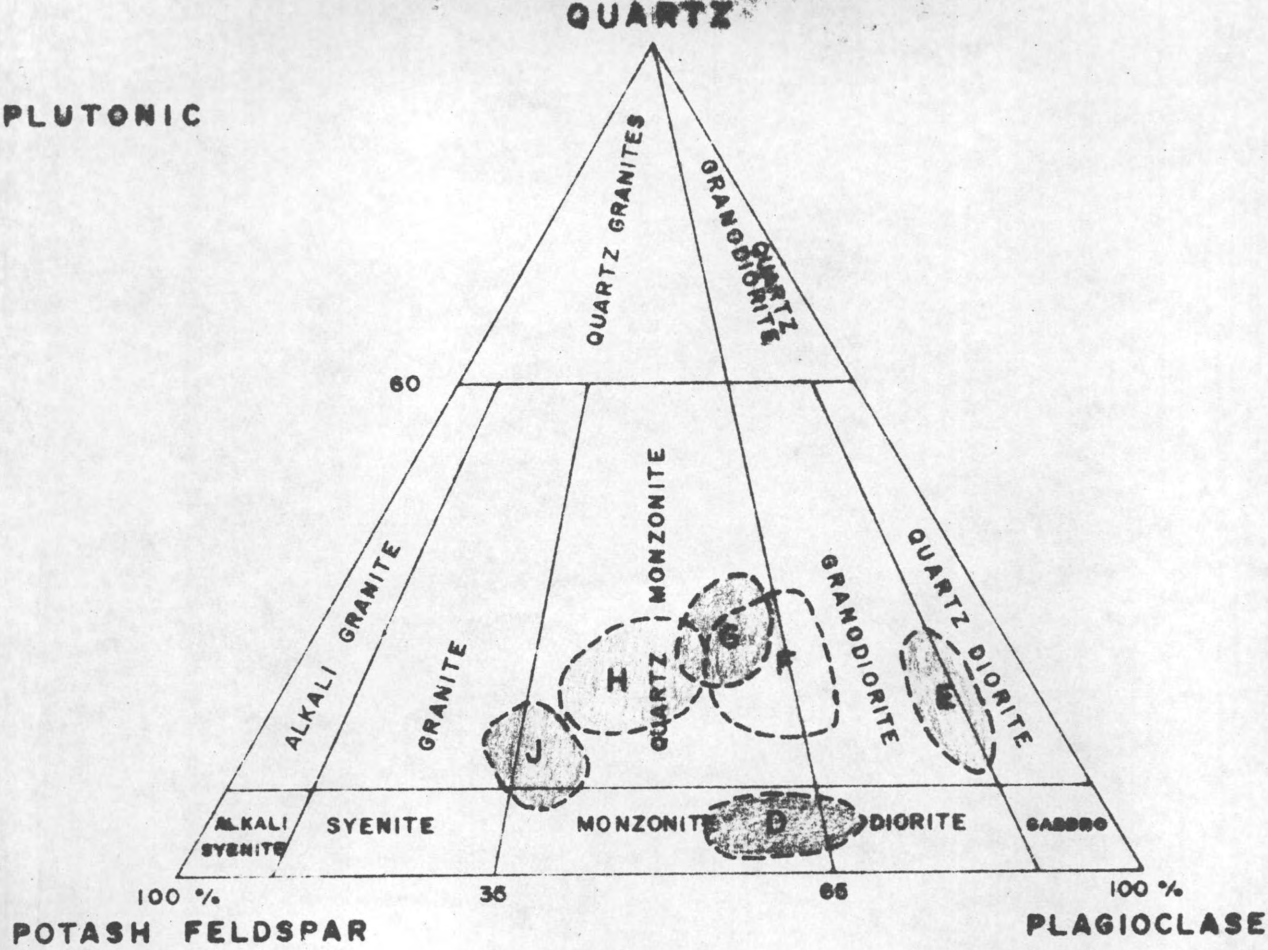
White, W.H., Thompson, R.H. and McTaggart, K.C. 1957 The geology and mineral deposits of Highland Valley, B.C.; Can. Min., Met. Bull., Vol. 50, No. 544, pp. 487-504.

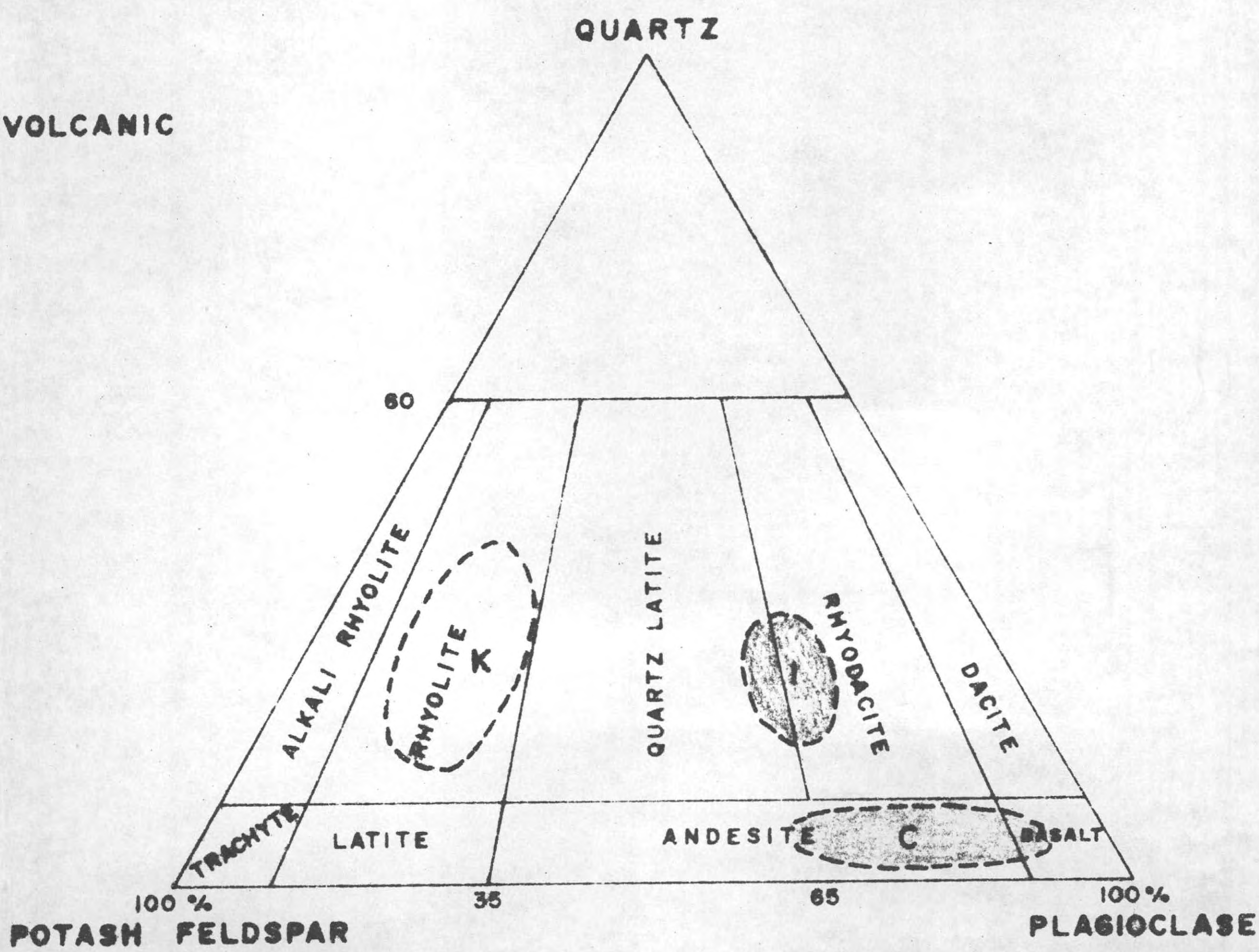
Williams, H., Turner, F.J., and Gilbert, C.M. 1954 Petrography, An Introduction to the Study of Rocks in Thin Sections; W.H. Freeman and Comp., San Francisco, p. 20.



Appendix I. Chart for visual estimation of roundness and sphericity of grains. (After Krumbein and Sloss, 1963.)

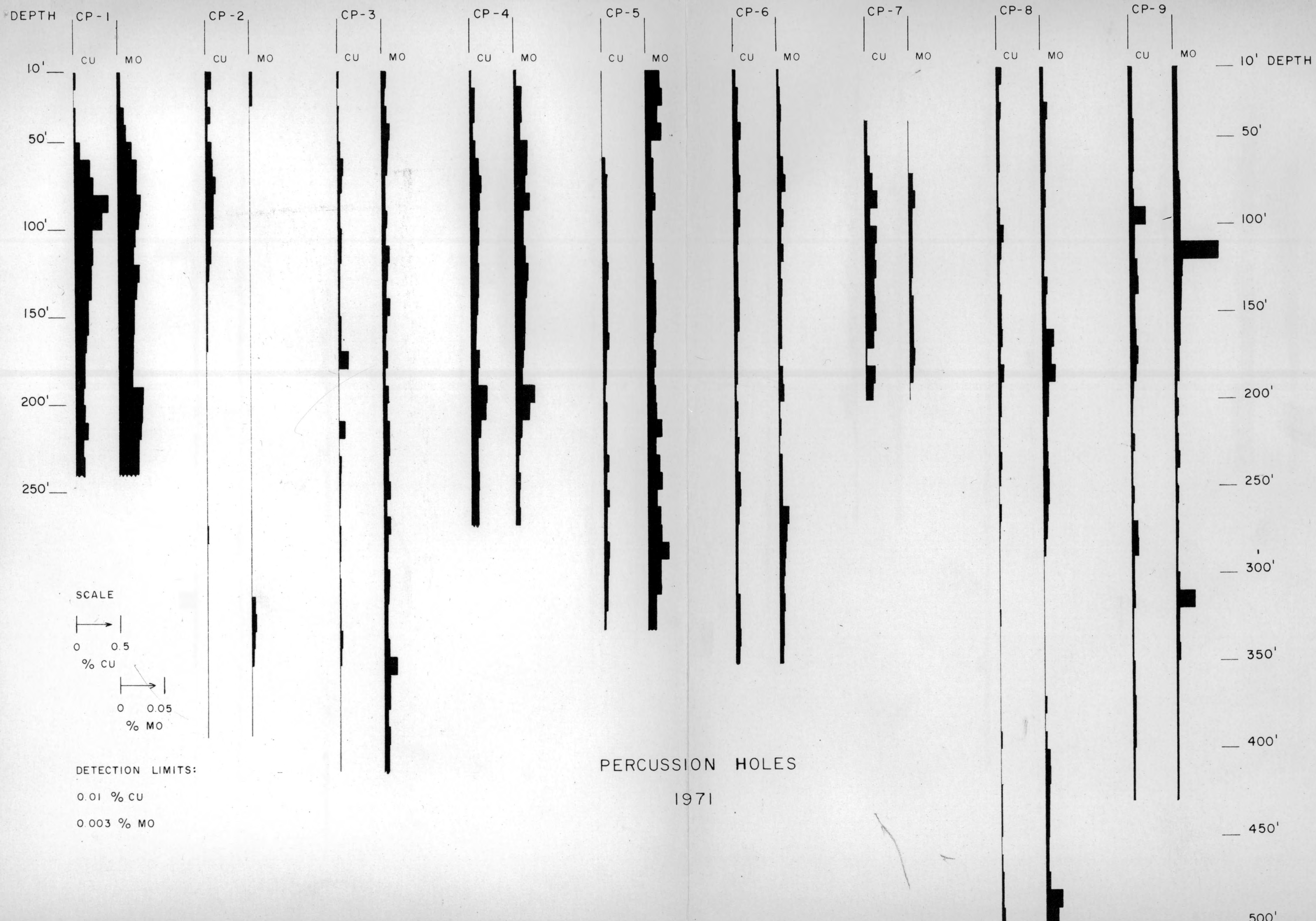
APPENDIX 2
ROCK CLASSIFICATION





(AFTER D.W. PETERSON. A.G.I. Volume V. Number 6.)

CP-1	232N/ 196W	
CP-2	216N/ 214W	
CP-3	176N/ 152W	
CP-4	228N/ 174W	
CP-5	208N/ 182W	
CP-6	260N/ 244W	
CP-7	268N/ 250W	
CP-8	324N/ 224W	
CP-9	336N/ 216W	
CD-1	224N/ 208W	N45°E , -45°
CD-2	332N/ 200W	190° , -45°



DETECTION LIMITS:

0.01 % CU

0.003 % MO

PERCUSSION HOLES

1971

Mineral. Deposita (Berl.) 9, 243–252 (1974)

Factor Analysis of Stream Sediment Geochemical Data from the Mount Nansen Area, Yukon Territory, Canada

Rudolf Saager
Heidelberg, Germany

Alastair J. Sinclair
Vancouver, Canada

Q- and R-mode factor analytical studies were made of 158 stream sediment samples from the Mount Nansen area, Yukon Territory, analyzed for Cu, Pb, Zn, Mo, Ni, Ag, and Sb. R-mode results were more clear-cut than were Q-mode in terms of ease of interpreting geological significance of individual factors, although results of both methods were very comparable. The 3-factor R-mode model accounted for 79.9 percent of the variation in the data. Factor 1, a Pb—Zn—(Ag) factor correlated with Mount Nansen volcanic rocks and particularly with known Pb—Zn—Ag—Au veins within those rocks. Factor 2, a Cu—Mo factor correlated with porphyric intrusions known to contain Cu—Mo mineralized zones. Factor 3, an Sb—(Ag) factor is, as yet, not adequately explained in terms of geology. The main additional contribution of the Q-mode study is the communalities. Samples that depart from the norm (i.e. do not agree well with the 3-factor model) are readily apparent because of low communalities and must be considered "anomalous" in the general sense until an adequate explanation for this difference is found.

Introduction

As part of a more extensive exploration program, a stream sediment survey was undertaken during the summer of 1970, in a 70 square km area centred near Mount Nansen, Yukon Territory. The area is at the southeastern end of the Dawson Range, 150 km northwest of Whitehorse (Figure 1). A general description and analysis of the exploration program has been presented by Bianconi and Saager (1971). About 200 stream sediment samples were obtained during the survey, of which 158 that were analyzed for Cu, Pb, Zn, Mo, Ni, Ag, and Sb, form the basis of the present study. Bianconi and Saager (1971) give a brief account of analytical procedures and precision. Precision at the 95 percent confidence level is between 15 and 25 percent for all elements except antimony which has a precision of about 50 percent.

A simplified geological map of the area is shown in Figure 2. The oldest rock unit known in the area is the *Yukon Group* consisting of quartz-hornblende gneiss, biotite schist and amphibolite, probably of late Precambrian age. Overlying the Yukon Group unconformably is a thick sequence of basalt and andesite porphyries that comprise the *Mount Nansen Group* of Jurassic to early Cretaceous age. Late Mesozoic and Tertiary intrusive bodies cut the two preceding groups. Plutonic rocks are thought to be part of the *Coast Range Batholithic Complex*. These three major rock units have been intruded by numerous quartz-feldspar porphyry masses with circular to elliptical areas of exposure that range in diameter from 30 to 1500 metres.

A system of northwest striking, high angle faults offset the preceding units, and some of these structures are mineralized (Saager and

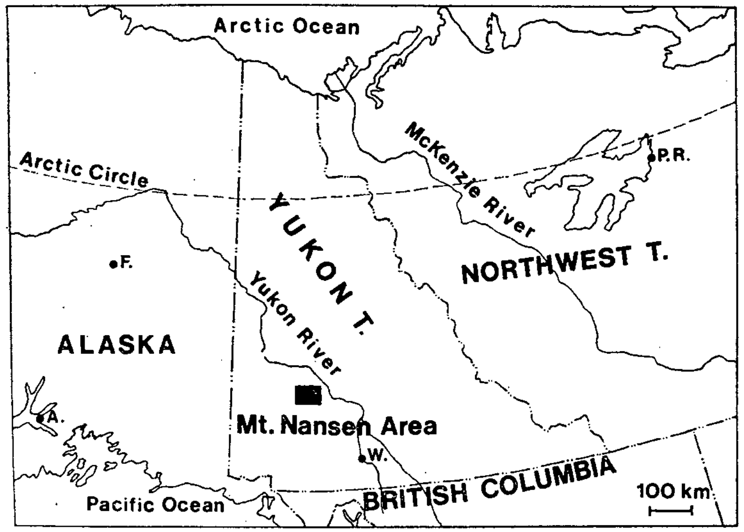


Fig. 1. Location of Mount Nansen area

BIANCONI 1971) A second, younger system of high angle faults striking northeasterly cuts country rock and mineralized veins.

Table 1. *Means and standard deviations, arithmetic and logged (base 10) data*

Element	Arithmetic (ppm)		Logarithmic (Base 10)	
	Mean	Std. Dev.	Mean	Std. Dev.
Cu	33	41	1.302	0.412
Mo	1.9	2.9	—1.027	2.249
Pb	21	16	1.242	0.261
Zn	55	28	1.686	0.232
Ni	8.7	2.7	0.923	0.215
Ag	1.15	0.69	—1.939	0.608
Sb	3.7	2.2	0.100	1.547

Frequency Distributions

Means and standard deviations for all variables are listed in Table 1. All distributions were treated by *chi square analysis* to determine whether or not they were approximated adequately by either normal or lognormal distributions. Using the chi square criterion, we found that Cu, Pb, and Zn are best approximated by lognormal distributions, Ag, Sb, and Ni approximate normal distributions, and Mo can be described equally well by either a normal or lognormal distribution. Such a procedure assumes that only a single population exists for each element. To check this supposition, cumulative probability plots were constructed (LEPELTIER 1969). Considerable evidence exists that the majority of minor element populations are positively skewed (e.g. SHAW 1961). Consequently, we were concerned about the possibility that for any particular element two or more overlapping distributions, each positively skewed, might produce what superficially appeared to be a single population with an apparently normal distribution. Log probability plots shown in Figure 3 for all seven elements, indicate the likelihood that multiple populations are represented by those variables for which arithmetic data seem to approximate normal distributions on the basis of chi square analysis. A more thorough treatment would have been to group the data on the basis of rock type predominating in the drainage basins of each stream sediment sample. This was not possible in the present case because the number of samples per group would have been too small for analysis on probability plots.

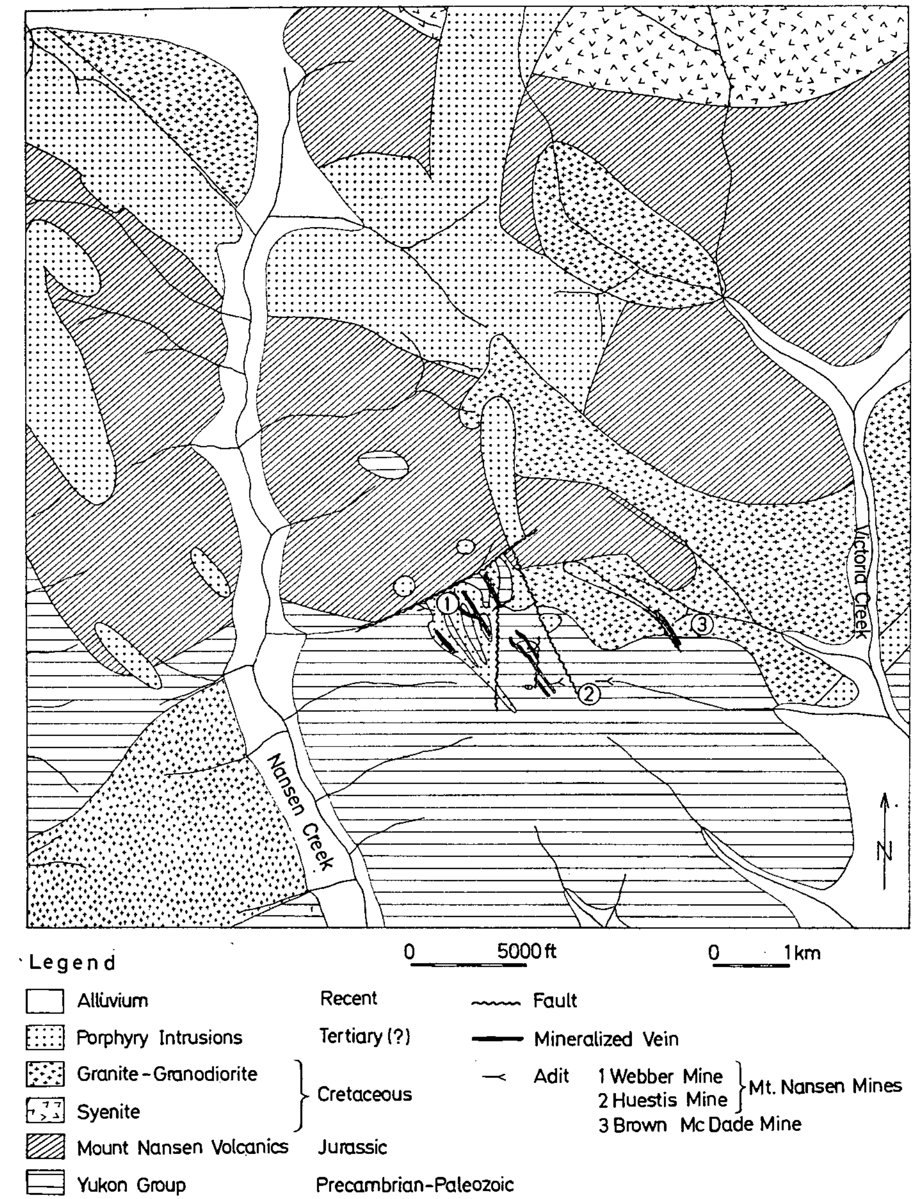


Fig. 2. Simplified geological map of the Mount Nansen area (after SAAGER and BIANCONI 1971)

Univariate Analysis

In the foregoing section we have concluded that all variables approximate a lognormal distribution or mixtures of lognormal distributions (see also BIANCONI and SAAGER 1971). An example is shown in Figure 4 for Cu values in stream sediments and illustrates the strong positive skewness.

This univariate analysis proved useful in the Mount Nansen area in permitting rapid recognition of significant thresholds between

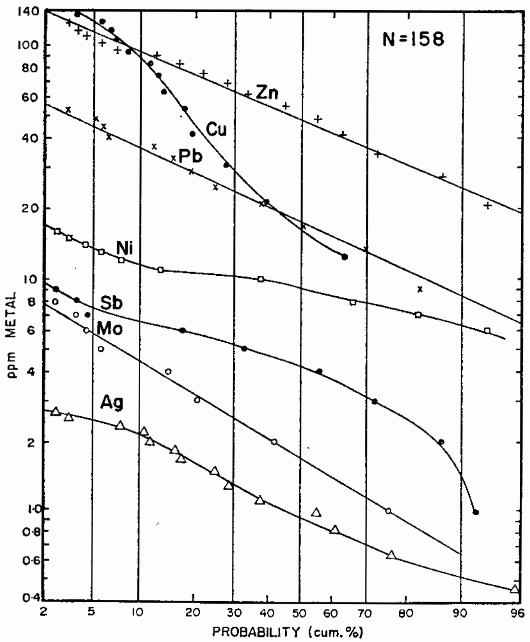


Fig. 3. Cumulative probability graphs of seven variables (Cu, Zn, Pb, Ni, Sb, Mo, Ag) used in this study

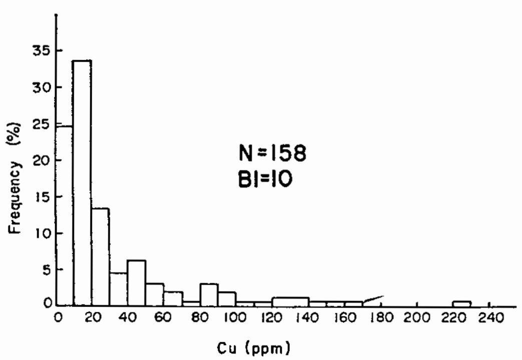


Fig. 4. Histogram oj 158 stream sediment Cu values, Mount Nansen area

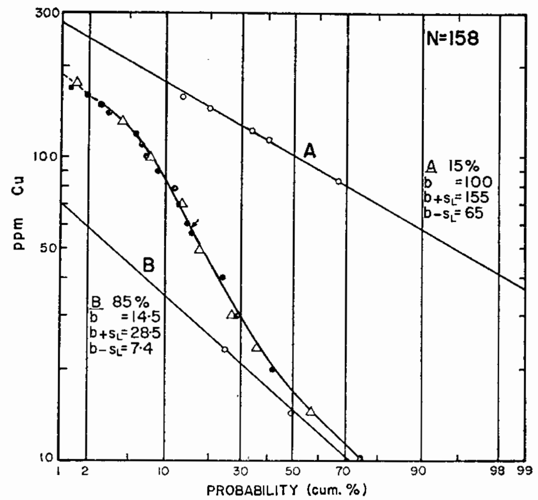


Fig. 5. Partitioned cumulative probability plot for 158 stream sediment Cu values, Mount Nansen area

background and anomalous values. For example, in the partitioned probability plot of Cu (Figure 5), a change in direction of curvature is apparent at the 15 cumulative percentile indicating the presence of 2 lognormal populations. In fact, two ideal populations, A and B, that mix in the proportions 15 percent A and 85 percent B, can be extracted from the curved distribution of actual data. Such an analysis allows one to estimate the relative proportions of the two populations in any arbitrarily chosen range of values, and on this basis relative priorities for follow-up exploration can be assigned. A formal procedure for use of probability plots in defining thresholds and priorities is given by SINCLAIR (in press). An analysis of this sort, while more refined than the qualitative subjective approach in common usage, nevertheless affords an opportunity of *missing* significant anomalies. The reason is apparent when one considers that a certain probability exists that some anomalous values will occur in the range of background values. At best, these values will be given low priority for follow-up exploration, and at worst, they will be ignored. The foregoing is true even though the greatest care is taken in sample collection, chemical analyses, data plotting, and interpretation. One means of offsetting these difficulties to some extent at least, is through the use of multivariate statistical procedures. Furthermore, previous unpublished work by one of us (A. J. S.) has shown that stream sediment anomalies commonly are enhanced as a result of certain types of multivariate analysis. It is for these reasons that we have undertaken a detailed factor analysis of stream sediment data from the Mount Nansen area.

Factor Analysis

An ever increasing literature on factor analysis suggests that the technique is useful in evaluating multivariate geochemical data of various types (e.g. NICOL *et al.* 1969; SAAGER and ESSELAAR 1969; DAWSON and SINCLAIR, in press). Commonly it is possible to interpret the resulting multivariables (factors) in geological terms, such as processes or types. Thus one can investigate the extent to which individual samples reflect a particular process or end member rock type. The importance of this potential of factor analysis can be appreciated if one is able to define a factor that relates to "hydrothermal processes".

We will make no effort to describe factor analysis in rigorous mathematical terms. Such a goal is best served by appropriate texts (e.g. HARMAN 1960). We are more concerned with an intuitive appreciation of factor analysis with minor reference to mathematical aspects. A similar approach is used by NICOL *et al.* (1969) and SAAGER and ESSELAAR (1969).

The first essential step in any factor analysis is to obtain a correlation matrix. In *R-mode* a matrix of simple correlation coefficients is used, whereas in *Q-mode* a cos theta matrix is the basis of future manipulations. *R-mode refers to correlations between pairs of variables, whereas Q-mode deals with correlations between pairs of sample sites.* From this similarity or correlation matrix are extracted the principle components, a set of perpendicular axes in n-dimensional space arranged such that variance in the data is minimized. Any one of these principle components can be thought of as a multivariable since it is nothing more than a line in n-dimensional space and is therefore a linear combination of the original variables. Principle components are rotated according to specific mathematical criterion such as the varimax rotation that maximizes the variance, a useful means of picking out extreme or end-member combinations to aid interpretation of geological data. Each axis in this new position is known as a factor, the significance of which must be interpreted in light of the particular linear combination of simple variables that comprise the factor. In application of factor analysis to geochemical data, factors commonly include geochemically coherent elements that relate to underlying rocks or processes that have affected underlying rocks.

The relative contribution or importance of each factor at each sample site can be calculated. Such values can be contoured to delimit areas most affected by processes represented by the factors, e.g. hydrothermal activity, metasomatism, etc. For stream sediment data contouring is not the best method, and we adopt here a procedure using graduated circle sizes to reflect variations in factor values.

We have examined Mount Nansen stream sediment data using both R-mode and Q-mode factor analysis. Our purpose has been to examine and contrast the usefulness of both procedures as a general tool in the interpretation of multi-element stream sediment geochemical data.

R-Mode Factor Analysis

R-mode factor analysis examines the relationship among variables by analyzing a matrix of simple correlation coefficients for all pairs of variables considered. Standard programs available at the Computing Centre, University of British Columbia, were used to carry out the R-mode factor analysis. A preliminary study showed that Ni values obscured factor interpretation because Ni was represented as a small but not completely insignificant component of all important factors. Consequently, Ni values were deleted from further study. Results are summarized in tables 2 to 4 inclusive. Correlation coefficients are given in Table 2: Table 3 gives the eigenvalues for a 3-factor model, and Table 4 is the varimax factor matrix.

In Table 4, *communalities* represent the proportion of the variation in a given variable that is explained by the 3-factor model. *Note*

Table 2. *Correlation coefficients (based on 158 samples)*

	Cu	Mo	Pb	Zn	Ag	Sb
Cu	1.000					
Mo	0.500	1.000				
Pb	0.272	0.220	1.000			
Zn	0.047	–0.031	0.733	1.000		
Ag	0.361	0.196	0.564	0.379	1.000	
Sb	0.092	0.199	0.076	0.052	0.268	1.000

Table 3. *Eigenvalues and proportions*

Eigenvalues	2.424	1.407	0.961
Proportion of eigenvalues	0.404	0.235	0.160
Cumulative proportion of eigenvalues	0.404	0.639	0.799

Table 4. *R-mode varimax factor matrix*

Element	Factor 1	Factor 2	Factor 3	Communality
Cu	0.16188	−0.86173	−0.01738	0.76909
Mo	0.00589	−0.83989	0.14307	0.72592
Pb	0.90861	−0.20470	−0.00733	0.86752
Zn	0.90099	0.13360	0.03028	0.83054
Ag	0.65549	−0.31180	0.33563	0.63959
Sb	0.04699	−0.07155	0.97543	0.95880

that the total explained variance of this model is 79.9 percent. With the exception of Ag, the unexplained variance is equal to or less than the precision of analyses at the 95 percent level, and we conclude that any effort to interpret an additional factor from the data would not be advisable as it would over-extend the quality of the data. The table shows further that each factor consists of significant contributions from certain variables and less important to negligible contributions from others. In summary, we interpret Factor R-1 to be a Pb and Zn factor with a lesser but significant contribution from Ag, Factor R-2 as a Cu—Mo factor, and Factor R-3 as an Sb factor with a minor contribution from Ag. It is apparent that these groupings are precisely what one might expect from a geochemical point of view. The associations Pb—Zn—Ag, Cu—Mo and Sb—Ag, are well established in the literature on geochemistry and mineral deposits. Factor analysis, however, allows us to calculate a single value for each of these groupings. For example, instead of a quantitative analysis of three separate maps for Pb, Zn and Ag, we have established a linear relationship (factor) existing among these variables and a single map showing relative amounts of each factor can be examined. Such maps are shown in Figures 6, 7, and 8, for the

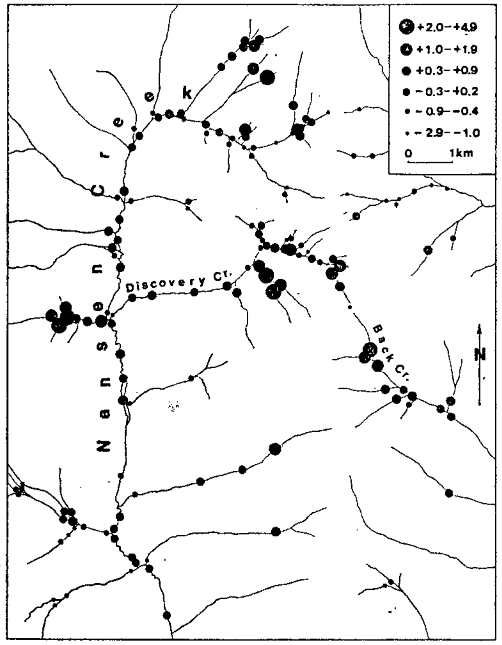


Fig. 6. R-mode factor 1 scores (Pb—Zn—Ag) in standard deviation units

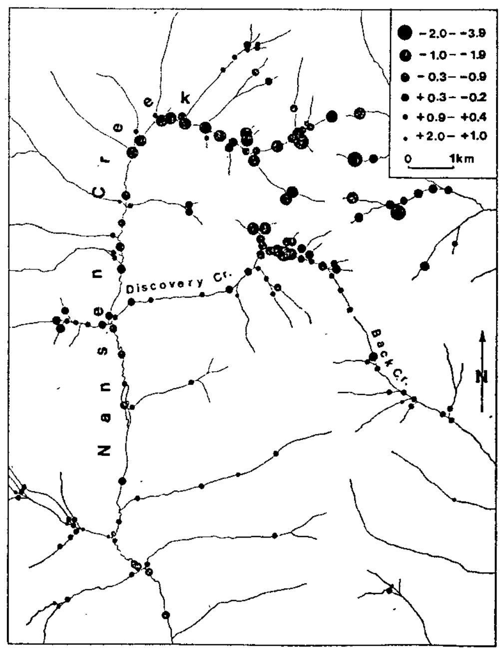


Fig. 7. R-mode factor 2 scores (Cu—Mo) in standard deviation units

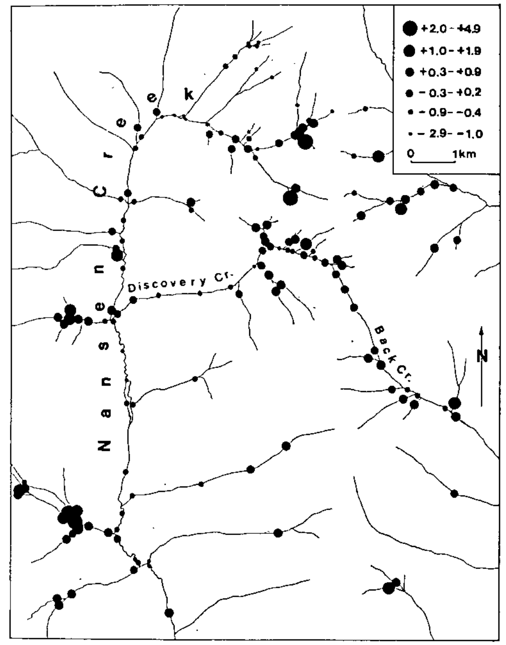


Fig. 8. R-mode factor 3 scores (Sb—Ag) in standard deviation units

three R-mode factors listed in Table 4. These maps should be compared with the general geological map of the region (Figure 2). Several points are worth noting:

1. The most pronounced factor R-1 values are from streams underlain by Mount Nansen volcanic rocks, although by no means all samples from such rocks have high Factor R-1 scores.

2. Many of the high factor R-1 scores correlate with known Pb—Zn—Ag—Au vein deposits such as those described by SAAGER and BIANCONI (1971).

3. Where several samples have been taken from one stream, and the upstream sample is relatively high, the remaining samples give lower and lower scores progressively downstream. This compares well with the general situation for anomalous values of individual elements and reflects dilution. Some reversals are present, of course, but these do not seem to be pronounced.

4. The samples and groups of samples with high factor scores correlate well with high values of the individual variables (Pb, Zn, and Ag) shown on maps previously published by BIANCONI and SAAGER (1971). In fact, virtually all anomalous samples on the three maps of single variables (See Figures 8, 9, and 10, BIANCONI and SAAGER 1971) show up on the factor map but do not show up on every single-variable map. The factor analysis has therefore been successful in compressing into a single map, all the anomalous samples indicated on three, single-variable maps.

5. As a rule, samples noted as anomalous on single variable maps are enhanced on the factor map. This is generally true in the situation where a factor consists of three or more variables because the anomalous sample is commonly high in several, though not necessarily all variables that constitute a factor.

Factor R-2 is essentially a Cu—Mo factor. Abundant high values are compared in samples in the northern part of the study area whose drainage basins are partly or wholly underlain by porphyritic intrusions. It was, in fact, the presence of these intrusions that lead to the geochemical survey from which data used in this study were extracted. One major aim of the survey was to define exploration targets for large, low grade Cu—Mo deposits. Additional exploration has been carried out in the area since our data were collected and although results are not generally available for publication, interesting Cu—Mo mineralization is known to occur in some of the areas underlain by porphyry intrusions and having high values of factor R-2. We conclude therefore that factor R-2 has provided a useful guide for further intensive exploration. A comparison of the factor R-2 map, with Figures 6 and 7 of BIANCONI and SAAGER (1971) for Cu and Mo respectively, lead to conclusions comparable to those expressed previously in our discussion of Factor R-1.

Factor R-3 consists essentially of Sb with a minor contribution from Ag, other elements being negligible. Consequently, little difference is to be expected between a map of R-3 values and a map of Sb values. Such is the case as can be seen by comparing Figure 8 with Figure 11 of BIANCONI and SAAGER (1971).

We have been unable to arrive with any certainty at a conclusion as to the significance of Factor R-3. Occurrences of Ag-bearing sulphosalts are known in the area (Saager and Bianconi 1971) but do not coincide with high factor R-3 values.

Table 5. *Varimax factor score matrix, Q-mode*

	Factor 1	Factor 2	Factor 3
Cu	−1.8875	0.8714	0.3393
Mo	−0.7677	0.2859	0.5019
Pb	−0.8596	−1.2698	−0.4064
Zn	−0.3579	−1.6254	−0.6305
Ag	−0.8433	−0.6526	0.7523
Sb	0.5117	−0.7052	2.1199

Table 6. *Partial Q-mode varimax factor matrix*

Spec. No.	Communality	Factor 1	Factor 2	Factor 3
1	0.5233	0.7118	0.0860	−0.0962
2	0.9259	−0.1770	−0.0651	0.9436
3	0.6403	−0.5732	0.2140	0.5158
4	0.6550	−0.2125	0.6971	0.3520
5	0.8920	0.4443	0.8006	0.2316
6	0.8755	−0.7120	−0.4043	0.4529
7	0.9229	−0.4600	−0.1361	0.8323
8	0.5078	−0.4265	−0.4347	0.3700
9	0.8591	0.6038	0.6746	−0.1986
10	0.8890	0.3314	−0.1942	0.8611
11	0.9485	0.0168	0.9676	−0.1095
12	0.9321	−0.1224	−0.2962	−0.9107
13	0.9625	−0.3963	−0.5073	−0.7403
14	0.8601	−0.5880	−0.5755	−0.4280
15	0.8335	−0.5548	−0.4414	−0.5752
144	0.9536	0.7232	0.4902	−0.4363
145	0.7411	0.8174	0.2216	0.1540
146	0.3028	−0.4625	0.1732	0.2426
147	0.4025	−0.4222	0.1122	0.4601
148	0.9532	0.6583	0.4876	−0.5312
149	0.9008	0.8511	0.2105	0.3635
150	0.9478	0.7269	0.4889	−0.4246
151	0.8031	0.2509	0.7606	0.4020
152	0.8522	−0.5022	0.2877	0.7192
153	0.9566	0.3436	0.8923	0.2057
154	0.3181	0.1461	−0.0932	0.5368
155	0.7961	0.0665	0.8835	−0.1058
156	0.3725	0.2039	0.4620	0.3428
157	0.5240	−0.5224	0.3389	0.3690
158	0.9004	−0.2984	−0.8948	0.1035
	Variance	31.907	27.532	20.906
	cum. var.	31.907	59.440	80.346

Q-Mode Factor Analysis

In Q-mode analysis a similarity measure must be obtained between samples rather than elements. This is achieved by measuring the angle between each sample pair where samples are plotted as vectors in n-dimensional space. Each coordinate or dimension represents one element. The cosine of the angle between two sample vectors is a measure of their similarity and all possible values give the so-called cos theta matrix.

Principal components are extracted and these are then rotated according to some mathematical criterion, in this case a varimax rotation. *A 3-factor model summarized in Tables 5 and 6 accounts for 80.3 percent of the variation in original data.* These 3 factors correspond in a general way to those obtained by R-mode analysis, but are less clear-cut than the R-mode factors. Note the main variables comprising each Q-mode factor:

Q-1: Cu (Pb, Ag, Mo)
Q-2: Zn, Pb (Sb)
Q-3: Sb (Ag)

It is evident that precisely identical factors have not been obtained by R-mode and Q-mode procedures. There is a general similarity, however, that carries over into maps of factor values. Q-mode maps are generally similar to those shown for R-mode results but are slightly more obscure. The major additional information provided by the Q-mode study is a map of communalities (Fig. 9). This map indicates the extent to which each sample departs from the general 3-factor model. Samples with high communalities are well explained by the 3-factor model whereas those of low communality are not. Low communality samples should therefore be investigated thoroughly to ascertain why they depart from the norm. Such samples are anomalous in the general sense of the word but of course there is no certainty that they are indicative of mineralized zones.

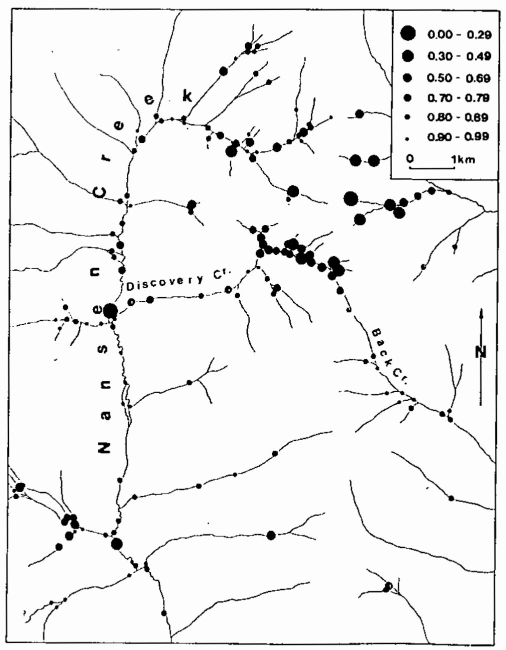


Fig. 9. Q-mode communalities

Conclusions

1. From an exploration point of view, the great advantage of factor analysis is that the study of many variables commonly can be reduced to a few. In the present case, seven initial variables were reduced to three (e. g. factor 1, a Pb—Zn—(Ag) factor; factor 2, a Cu—Mo factor; and factor 3, a Sb—(Ag) factor), of which two appear particularly important for mineral exploration (e. g. factors 1 and 2).

2. Factor analysis appears to result in no significant loss of information. In fact, our experience suggests that recognition of anomalous samples is enhanced by factor analysis. Consequently it permits recognition of some anomalous samples that might otherwise be missed. This is particularly important for samples within the ppm range of effective overlap of anomalous and background populations of individual variables.

3. In this study, we have found R-mode factor analysis to provide more easily and reasonably interpretable results than Q-mode factor analysis. In other unpublished studies, however, (e. g. Dawson and Sinclair, in press) we have found the reverse to be true. We therefore urge caution in rejecting one method in favour of the other without actually carrying out both analyses and comparing the results, especially in regard to the possibility to reasonably interpret them.

4. In this example, Q-mode communalities appear useful in outlining anomalous samples. Low communalities represent samples that fit a general mathematical model for the data *least well*. They are therefore different from the majority of samples and should be examined for the cause of this difference.

5. Factor analysis is obviously not the solution to all problems in interpretation of geochemical data. It is a complex subject, the interpretation of which is somewhat subjective. Perhaps, however, it is this very subjectivity that is one of its strengths, for it permits formulation and testing of geological models involving processes.

Acknowledgements

The field program that provided information used in this study was carried out by Gesellschaft für Metallwerte, Zürich, who have kindly granted permission for the publication of results. Computations were done on the IBM 360/67 computer at the University of British Columbia. Technical assistance of Mr. A. C. L. Fox is appreciated. One of us (A. J. S.) acknowledges the financial support of the National Research Council of Canada.

References

Bianconi, F., Saager, R.: Reconnaissance mineral exploration in the Yukon Territories, Canada. Schweiz. Mineral. Petr. Mitt. **51**, 139—154 (1971)

Dawson, K. M., Sinclair, A. J.: Factor analysis of minor element data for pyrites, Endako Molybdenum Mine, British Columbia, Canada. Econ. Geol. (in press)

Harman, H. H.: Modern factor analysis, 469 p. Chicago: Univ. Chicago Press 1960

Lepeltier, C.: A simplified statistical treatment of geochemical data by graphical representation. Econ. Geol. **64**, 538—550 (1969)

Nicol, I., Garrett, R., Webb, J. S.: The role of some statistical and mathematical models in the interpretation of regional geochemical data. Econ. Geol. **64**, 204—220 (1969)

Saager, R., Esselaar, P. A.: Factor analysis of geochemical data from the Basal Reef, Orange Free State goldfield, South Africa. Econ. Geol. **64**, 445—451 (1969)

— Bianconi, F.: The Mount Nansen Gold-Silver deposit, Yukon Territory, Canada. Mineral. Deposita (Berl.) **6**, 209—224 (1971)

SHAW, D. M.: Element distribution laws in geochemistry. Geochim. Cosmochim. Acta **23**, 116–134 (1961)

SINCLAIR, A. J.: Selection of threshold values in geochemical data using probability graphs. J. Geochem. Expl. (in press)

Received: February 27, 1974

Dr. R. SAAGER

Institute for Mineralogy and Petrology, University of Heidelberg, D-6900 Heidelberg, Federal Republic of Germany

Dr. A. J. SINCLAIR

Department of Geological Sciences, University of British Columbia, Vancouver 8, B. C., Canada

MOUNT NANSEN

The Mount Nansen property is situated 120 air miles northwest of Whitehorse and 28 miles west of Carmacks in the Yukon Territory. It lies with the Dawson Range, an area which was unaffected by the last period of glaciation. This prospect was acquired through a joint venture agreement between Area Exploration Company and Mount Nansen Mines Ltd. in 1971 in which Area could earn a minimum 75% interest in the property. After preliminary testing during the 1971 field season, a second joint venture was undertaken in 1972 with Getty Mining Pacific, Ltd. Under this agreement Getty could earn a 33.75% interest in the Mt. Nansen agreement reducing Area's position to a minimum 41.25% undivided interest.

The property has expanded from an original 234 full size and fractional claims to a total of 381 claims. The Mt. Nansen agreement does not include claims at southeast corner of the property on which an unsuccessful silver-gold mining operation had previously been attempted. Additional claims were acquired by staking fractions within the original claim block, extending the western boundary to cover a new copper-molybdenite zone, and by optioning 16 claims from Mr. Toni Wheeler and 7 mineral leases from Mr. Frank Goulter of Carmacks.

A fairly extensive work program during 1971, consisting of geological mapping, geochemical soil sampling, ground magneto meter, E.M., and I.P. surveying confirmed the presence of a "classic" porphyry type geological environment. A zone of varied porphyry intrusives characterized by geochemical and geophysical anomalies extends over a length of three miles in a northwesterly trend. Perhaps the most significant feature of this property is the very large area of favourable geology. Granodioritic and quartz-feldspar porphyry intrusives are considerably leached and altered, and are mineralized with copper-molybdenum and contain some precious metal values. Nine short percussion holes and two diamond holes, drilled in 1971, encountered altered, mineralized intrusive rock with some sections returning significant assays in copper and/or molybdenum. Approximately $156,000 including option payments was expended on this prospect in 1971.

During the 1972 field season 10 widespread vertical diamond holes were drilled testing parts of this zone. Every hole intersected pyritized, altered intrusive rock and variable amounts of copper and molybdenum sulphides. Two of the holes cut encouraging supergene copper blankets at shallow depths. Significant molybdenum values were associated with the copper. These two holes coupled with an earlier percussion hole with similar assays rim the western border of a large, altered silicified porphyry dome. An attempt was made to close this area to the east this year, but had to be postponed due to freeze-up.

In addition to the 1972 drilling, follow-up work on a strong silt geochemical anomaly resulted in the find of a mineralized area at the west edge of the property. Soil geochemistry and prospecting outlined an irregular zone some 3,600 feet long by 2,000 feet wide. Soils were anomalous in copper, molybdenum, lead, zinc, and silver. Pervasive, finely disseminated molybdenite and some copper mineralization was located in dacitic volcanic rock across the zone. The volcanics appear to be underlain by a porphyry intrusive plug. The lead, silver and zinc values in soils may represent zoned offshoots of a copper-molybdenum contact body.

These two areas require further testing by drilling. Also, a strong copper, molybdenum, lead and silver soil geochemical anomaly at the northwestern corner of the Mt. Nansen claim block and in part, lying on Mr. Toni Wheeler's optioned ground remains to be adequately tested. This anomaly has an extent of some 4,500 feet by 3,000 feet. To date, only two short percussion holes and one angle diamond hole have been drilled in this geologically favourable area.

The present I.P. data strongly suggests a closure in the pyrite halo to the northwest, similar to that in the southeast. This should be confirmed by further work and will probably present further targets in this largely overburden covered area.

Estimated 1973 Expenditures - $50,000

ROCK SUITE MT. NANSEN PROJECT

PORPHYRY EXAMPLES (TERTIARY) ?

D-68	Feldspar porphyry, minor mafics Light brown ground mass, fine grain silicious A - 180 ppm Cu B - 1.1% Cu
D-30	Rhyolite
M-1-2	Rhyolite, spatially related to Mt. Nansen volcanics, probably genetically related to porphyry related to acidic porphyry stock mapped as such
D-61	Typical unaltered quartz feldspar porphyry found along South bank of Eva Creek (164N, 153W) Minor hornblende mafics, disseminated pyrite
D-38	Quartz - feldspar porphyry Relatively unaltered, minor mafics found East of siliceous dome
Y-42	Quartz - feldspar porphyry Dark grey matrix, unaltered

VOLCANIC EXAMPLES (EARLY MESOZOIC)

Y-25	Agglomerates South of porphyry intrusion. Mt. Nansen volcanics
Y-9	Basalt
D-21	Pophritic andesite Showing flow banding? typical of Mt. Nansen volcanics
D-20	Porphyritic andesite Located North of porphyry

BRECCIA EXAMPLES (TERTIARY)

D-52	Breccia, quartz porphyry fragments Pebble size, dark grey smoky quartz matrix Found in two areas of 400' x 200' each
D-57	Breccia ? Dark grey black basic matrix, fine grained 100' South West of 200N, 200W Breccia pipe

DIORITE EXAMPLES (EARLY MESOZOIC)

D-56	Hornblende diorite Spatially and genetically related to volcanics, found between andesites and intrusive granodiorite Located South of porphyry stock

Y-8	Hornblende diorite Spatially and genetically related to volcanics, found between andesites and intrusive granodiorite Located west of stock
D-35	Contact ix showing granodiorite - diorite contact, thus not a drill phase of batholith

GRANITES (MESOZOIC)

D-65	Medium grain equigranular granodiorite contacts with porphyry at confluence of Eva Creek with Victoria Creek
D-78	Biotite - hornblende granodiorite 264 N, 240W. Associated with anomally near Courtland Creek SW of pluton
D-28	Hornblende granodiorite (top of Caribou Mtn.)
D-77	Biotite hornblende granodiorite (North of stock)
D-58	Hornblende granodiorite (East of stock)
Y-33	Hornblende - biotite granodiorite (South of stock)
D-27	Hornblende granodiorite (North West of stock - Caribou Mtn.)

METAMORPHIC (PALEOZOIC PRECAMBRIAN ?)

Y-27	Hornblende - (a) gneiss (b) schist Found South of stock, ~~pendant~~ WINDOW in volcanics

HORNBLENDE - PLAGIOCLASE PORPHYRY

D-83	Hb-plag porphyry, intrusive, NE of silicious dome, large hornblende phenocrysts (related to batholith ?) aphophyses found in volcanics

DYKES

D-23	Hb-plag dyke North of stock cutting volcanics Related to above intrusion
Y-11	Hb-plag porphyry dyke North of pluton
Y-24	Quartz - feldspar porphyry dyke Possibly related to porphyry stock Cut volcanics to North
Y-13	Quartz - feldspar porphyry dyke As above

MINERALIZATION SUITE

D-90 Silicified quartz - porphyry
Disseminated chalcopyrite, pyrite and malachite found on west side of large silicious dome
Representative of mineralized float found at widespread intervals around dome (220N, 181W)

D-69 Silicified quartz - porphyry
Disseminated pyrite, chalco, malachite
Amount of disseminated pyrite representative of unaltered areas of porphyry stock (218N, 188W)

D-53 Silicified quartz porphyry, boxwork fracturing, pyrite filled showing at least two periods of mineralization
Located on North bank of Discovery Creek 800' SW of Breccia pipe and as float in Discovery Creek

D-91 Textbook example of transported limonite (pyrite) vugs void, Rx stained light brown
Porphyry Rx leached and clay altered
Located between East and South fork of Nansen Creek & at (228N, 212W)